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Geosciences Roadmap

for Research Infrastructures 2025–2028
by the Swiss Geosciences Community

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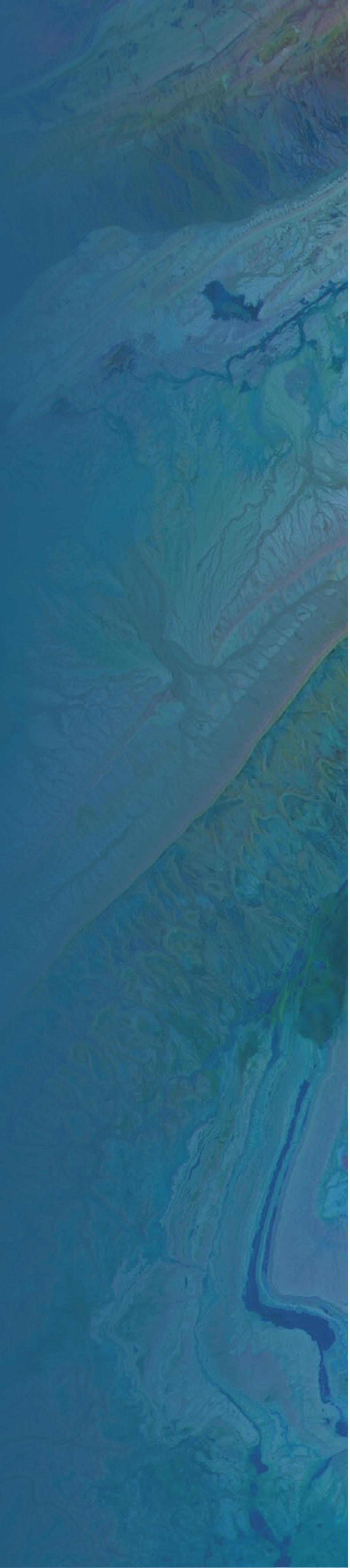


Geosciences Roadmap

for Research Infrastructures 2025–2028
by the Swiss Geosciences Community

Content

1 Executive Summary

This roadmap is the product of a grassroots effort by the Swiss Geosciences community. It is the first of its kind, outlining an integrated approach to research facilities for the Swiss Geosciences. It spans the planning period 2025–2028.

Swiss Geoscience is by its nature leading or highly involved in research on many of the major national and global challenges facing society such as climate change and meteorological extreme events, environmental pollution, mass movements (land- and rock-slides), earthquakes and seismic hazards, global volcanic hazards, and energy and other natural resources. It is essential to understand the fundamentals of the whole Earth system to provide scientific guidelines to politicians, stakeholders and society for these pressing issues. Here, we strive to gain efficiency and synergies through an integrative approach to the Earth sciences. The research activities of individual branches in geosciences were merged under the roof of the **'Integrated Swiss Geosciences'**. The goal is to facilitate multidisciplinary synergies and to bundle efforts for large research infrastructural (RI) requirements, which will result in better use of resources by merging sectorial activities under four pillars. These pillars represent the four key RIs to be developed in a synergistic way to improve our understanding of whole-system processes and mechanisms governing the geospheres and the interactions among their components. At the same time, the roadmap provides for the required transition to an infrastructure adhering to FAIR (findable, accessible, interoperable, and reusable) data principles by 2028.

The geosciences as a whole do not primarily profit from a single large-scale research infrastructure investment, but they see their highest scientific potential for ground-breaking new findings in joining forces in establishing state-of-the-art RI by bringing together diverse expertise for the benefit of the entire geosciences community. Hence, the recommendation of the geoscientific community to policy makers is to establish an integrative RI to support the necessary breadth of geosciences in their endeavor to address the Earth system across the breadth of both temporal and spatial scales. It is also imperative to include sufficient and adequately qualified personnel in all large RIs. This is best achieved by fostering centers of excellence in atmospheric, environmental, surface processes, and deep Earth projects, under the roof of the 'Integrated Swiss Geosciences'. This will provide support to Swiss geosciences to maintain their long standing and internationally well-recognized tradition of observation, monitoring, modelling and understanding of geosciences processes in mountainous environments such as the Alps and beyond.

The Amazon River and Its Surrounding Lakes
(photo: NASA)

2 Findings and Recommendations

Geo-OBSERVE — Integrated Long-Term Observatory

Finding 1: The existing large research infrastructure (RI) in Switzerland can only partially cover the large spectrum of variables required to understand the diversity and the complexity of processes of the Earth system. This requires the fostering of synergies between different disciplines by applying a multidisciplinary holistic approach across a sufficient set of strategically placed monitoring sites combined with innovative monitoring designs and sensor technologies suitable for long-term observations.

Recommendation 1: It is recommended to establish a complementary and innovative new large infrastructure in the form of an Integrated Long-term Observatory (Geo-OBSERVE) with a sufficient set of well-placed monitoring sites, adaptive monitoring designs, and a powerful network of permanent sensor systems. The Alpine region, being highly relevant not only for Switzerland but also for many other mountainous countries, and a testing lab for climate change and air pollution effects, should play a major role in this Geo-OBSERVE, integrating natural hazards and biogeochemical cycles, including hydrological (H_2O), carbon (C), nutrient (N, P), environmental pollutants, and more.

Finding 2: Processes in geosciences often exhibit small but lasting trends overlain by short-term variability. Thus, research infrastructure for long-term observations is key for identifying and quantifying changes. Swiss geosciences have a long tradition of multi-year observations of unprecedented length and quality. Currently, several national research infrastructures (RIs) are operational with close ties between national and international scientific communities within the European arena.

Recommendation 2: Advanced Swiss RIs that are well connected with their respective international (European) RI network (ICOS, ACTRIS, eLTER, SwissOGS, EPOS, ARES) should receive the required funding and coordination to sustainably contribute at the highest quality level and with the best visibility through the Swiss national roadmap.

Geo-MOBILE — Mobile Monitoring Infrastructure

Finding 3: With the technical advances of mobile sensors, the advent of smaller devices and efficient data acquisition solutions, short-term, targeted investigations of environmental variables can best complement our knowledge and stationary long-term observations. The goal is to foster profound understanding of highly variable structures and processes at much higher spatial and temporal (4-D) resolution. A tailored instrument facility should cover a broad spectrum of transients, essential in many processes and feeding new discoveries.

Recommendation 3: It is recommended to establish a highly sophisticated mobile observational facility equipped with a large number and a large variety of sensors. Such a versatile Mobile Monitoring Infrastructure (Geo-MOBILE) of distributed sensor arrays will significantly catalyze synergies between all research groups and components of the RI. This would be of strategic importance to strengthen the Swiss geosciences at the international level.

Geo-TIME — The Swiss Geo-TIME Facility

Finding 4: Determining timescales and process rates at the highest possible precision and accuracy, across the scales from near-instantaneous up to the age of the Earth, is a fundamental aspect of the geosciences. Hence, it is necessary to expand the capabilities of Swiss Geosciences dating facilities and include emerging geochronological techniques, including those that record processes operating on short time scales near the Earth surface. Laboratories dedicated to measuring timescales and rates are costly and time-consuming facilities. This is a major limiting factor in acquiring chronological information on rates of geologic and environmental processes. In order to better understand the timing and rates of events that shape Earth in the present and its past, much higher temporal resolution of novel instrumentation is required.

Recommendation 4: It is recommended to build a large RI that integrates multi-user facilities in a consortium dedicated to the determination of timescales of processes in Geosciences (Geo-TIME) at the highest possible quality on an international level. This requires the inclusion of long-term funding of highly-trained technical staff, which will be crucial to future breakthroughs and swift response of the geosciences to societal issues.

Geo-DATA — Geosciences Data Infrastructure

Finding 5: Geodatasets are produced at an increasing pace as part of geoscientific research. Yet, these datasets are often stored in a large variety of formats and scattered among different platforms. Furthermore, there is a lack of integration, coordination and harmonization of data management on an international level. This situation, and the lack of trained and appointed data scientists, impedes the findability, usability and curation of digital geoscientific datasets, and, as a consequence, obstructs interdisciplinary and innovative Swiss geoscientific research as a whole.

Recommendation 5: It is recommended to develop a Geo-DATA platform to unify the access to the large variety of geoscientific datasets. This platform will serve as the Swiss national hub for the management of digital geoscientific datasets and will provide capabilities for the harmonization, dissemination, long-term archiving, and collaborative analysis of data. Tailored interfaces will allow users to carry out analyses and simulations in an integrated manner. The platform will be connected to other national and international data infrastructures und thus will enable unprecedented synergies. It will fulfill the aim the Swiss National Sciences Foundation and other funding agencies to provide public access to research findings and data and guarantee fair data access.

Finding 6: Professional sample curation and storage facilities, meeting the FAIR principles[1], international and SNSF standards, are currently lacking across the Swiss Geosciences landscape. Investment in centralized and scientifically managed sample storage and curation facilities suited to provide physical and metadata storage as well as initial sample documentation is considered a necessity. Most urgently, curation and storage facilities are required for sediment and permafrost cores and associated samples.

Recommendation 6: It is recommended to establish a centralized Swiss curation and storage facility for unique geo-samples of Swiss or international importance as an important component of the Geo-DATA facility. Such a facility would benefit the existing and newly designed research projects on both national and international levels while providing the means for professional sample and data curation, and interaction with the SwissCollNet/SwissBioColl initiative and other national initiatives for sample curation. In addition, such a facility would also foster collaborative and interdisciplinary research endeavors with strong links to the bio- and archeological sciences.

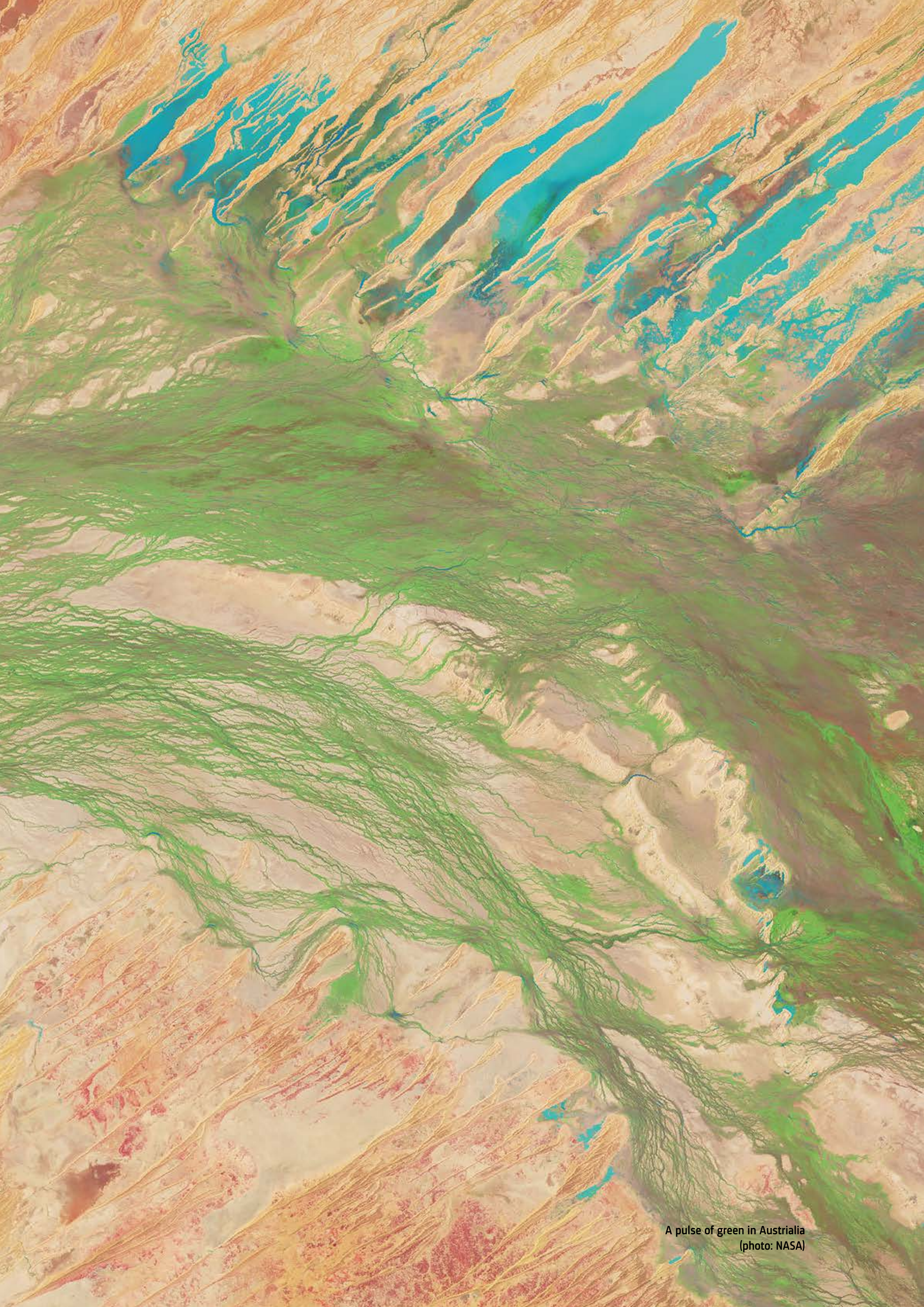
Churning in the Chukchi Sea
(photo: NASA)

3 SCNAT Foreword

The present roadmap for future large research infrastructures represents the view of the Swiss scientific community in the field of geosciences. It is a formal element of the process to elaborate the 'Swiss Roadmap for Research Infrastructures 2023' according to Swiss law (art. 41 Federal Act on the promotion of research and innovation; art. 55 of the corresponding Ordinance). The roadmap describes the community needs in terms of national or international research infrastructures for the funding period 2025–2028. It shall serve as an additional basis for decision-making on new or major upgrades of national infrastructures and/or major participations in international network infrastructures and user facilities.

The responsibility for the elaboration of the 'Swiss Roadmap for Research Infrastructures 2023' rests with the State Secretariat for Education, Research and Innovation (SERI). It has thus launched a process that includes: (phase 1) the selection of infrastructures by the ETH Board and swissuniversities, (phase 2) the evaluation by the Swiss National Science Foundation, and (phase 3) the assessment of feasibility once more by the ETH Board and swissuniversities. The outcome will be submitted to the Federal Council for consideration and decision in the context of the Dispatch on Education, Research and Innovation 2025–2028. This entire process is complemented by a preparatory phase to establish the needs of the various scientific communities. The SERI has formally given a mandate to the Swiss Academy of Sciences (SCNAT) for the elaboration of these discipline-specific community roadmaps, including the present one.

SCNAT has initiated the work to elaborate such discipline-specific community roadmaps in the fields of biology, geosciences, chemistry, and in sub-fields of physics in the last quarter of 2018. Its Board defined a process that provided for an overall strategic project lead and for community-specific sub-projects, all lead by acknowledged researchers. The entire process was modelled on the long-standing experience of SCNAT in the fields of astronomy and physics, where roadmaps for research infrastructures had been elaborated in earlier years by the various communities that were assembled for that purpose around a so-called 'round table'. Accordingly, starting in 2019, such round tables were also established in biology, chemistry and geosciences. In the past two years, hundreds of researchers were invited to take part in this process and dozens of them actively participated in each of the various round tables. Whereas this effort was run under the overall responsibility and guidance of SCNAT, including the provision of considerable scientific, editorial and administrative manpower by its office, the final result must be considered a genuine bottom-up contribution by the various scientific communities.



A pulse of green in Austrialia
(photo: NASA)

4 Preface

The roadmap at hand has evolved through a bottom-up process, initiated by SCNAT. Using the database of the SCNAT, over 300 experts were invited to participate. Based on this first grassroots meeting, the following six disciplinary working groups were established: Atmosphere, Earth Surface, Geophysics and Geodesy, Solid Earth, Geodata, with the sixth working group charged to focus on interdisciplinary aspects. Kick-off meetings for each group were initiated in January 2020, inviting again ca. 340 researchers (professors from ETH/swissuniversities or group leaders from research institutes) to participate in the SCNAT meetings. The chairs and co-chairs of these working groups frequently met to discuss the most urgent need for large infrastructure in Geosciences.

The working groups recognized the urgent need to develop a holistic approach for geosciences, which allows capturing and providing an improved understanding of large-scale processes that shaped the past and will shape the future of Planet Earth. Such an approach needs to integrate fundamental and applied research on the geospheres of Earth, each one with its own challenges, characteristic for its environment, but interacting with the other spheres on varying spatial and temporal scales. Earth science processes span many orders of magnitude in scales of the time-space continuum. To cope with these dimensions and with the diversity of the objects studied – from atoms and molecules, to minerals, rocks, ice, water, organisms and atmosphere – geosciences research rests on the tools developed by physics, geochemistry, biology, and mathematics to monitor the evolution of Earth, to read the geo-archives and understand the governing processes. The observations and data are bound together with theory, concepts and simulations.

The roadmap for large research infrastructures for 2025–2028 presents an integrative approach including the most urgent infrastructure requests, supported by 4 pillars: **1) The Integrated Long-term Observatory (Geo-OBSERVE), 2) The Mobile Monitoring Infrastructure (Geo-MOBILE), 3) The Swiss Geo-TIME Facility, and 4) The integrated Data Infrastructure for the Geosciences (Geo-DATA) (Fig. 1).** These infrastructures are conceived as distributed or centralized infrastructures to foster a strong collaborative national geoscientific community, attractive for international links.

The role of SCNAT was to provide support to the process via guidance, coordination and sharing of experience and best practices. It directly assisted the work of the round tables by organizing meetings, editorial work and the final layout and printing of the document. As foreseen in the SCNAT quality assurance procedures, members of the Executive Board oversaw the writing process to verify that the views expressed in the roadmaps are based on broad consultation of the scientific community and are independent from potential external influences. This roadmap is the result of this process and presents the vision of researchers for the future development of Geosciences in Switzerland.

Lighting the Edge of the Roof
(photo: NASA)

5 Purpose and Scope

The Swiss geosciences roadmap illustrated in Fig. 1 was elaborated based on the bottom-up procedure indicated in chapter 4 and hence provides a consolidated view of all geosciences in Switzerland. It is the first roadmap developed for Swiss Geosciences ever. It highlights the current research infrastructure needs to promote the Swiss presence in highly competitive research domains requiring large infrastructures and to foster successful Swiss participation in selected, top-notch international research programs, with the opportunity to train the next generation of scientists. It considers the central role of geosciences in developing a clean environment and responding sustainably to the needs of the society to rapidly provide information on Earth system changes. The community is convinced that boosting basic and applied geosciences based on monitoring and process-oriented research will provide society with well-founded answers to environmental problems. Pillar I (Geo-OBSERVE), integrates and boosts the unique long-term observation efforts and strengthens the leading role of Swiss Geosciences in international observation networks. Pillar II consists of a multifaceted, Mobile Infrastructure which allows temporary Monitoring (Geo-MOBILE), which is necessary to address emerging or short-term events at high resolution. Pillar III, (Geo-TIME) is a distributed facility designed to develop techniques and methods assessing the duration and age of geoscientific processes. It houses highly specialized laboratories where timescales and rates can be determined with the highest precision and accuracy. Pillar IV, Data Infrastructure for the Geosciences (Geo-DATA) is designed to provide large-scale open data and analytics capacity for linked geodata as well as storage facility for unique solid and liquid physical samples from primarily national, but also international, exploration efforts.

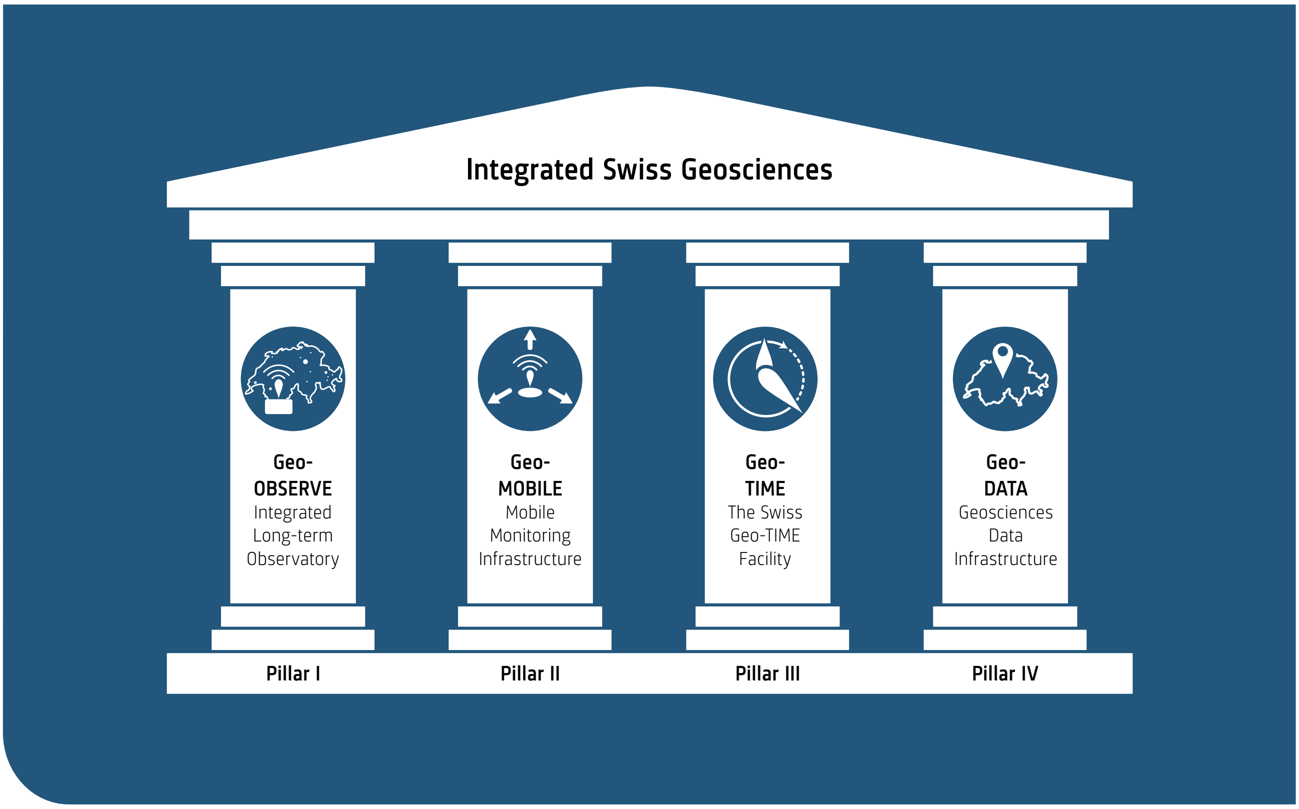


Fig. 1: The 2025–2028 Integrated Swiss Geosciences is built upon 4 thematic pillars that provide the basis for a state-of-the-art multidisciplinary integrated and harmonized geoscientific research environment. Pillar I, Integrated Long-term Observatory (Geo-OBSERVE) integrates the unique longterm observation efforts that make Switzerland one of the most data rich areas on Earth. Pillar II consists of a multi-faceted, Mobile Infrastructure which can be deployed for temporary Monitoring (Geo-MOBILE). Pillar III, Geo-TIME facilities (Geo-TIME) consists of a distributed network of state-of-the-art Swiss facilities to determine timescales and rates of geoscientific events. The final pillar IV, Data Infrastructure for the Geosciences (Geo-DATA) is designed to provide a large-scale open data and analytics facility for linked geodata, as well as storage facility for unique physical samples.

Grosser Aletschgletscher
(photo: NASA)

6 Introduction

Many of the greatest challenges for society in the next 50 years necessitate fundamental research in the Earth and environmental sciences. Society expects geosciences to provide answers to issues related to sustainable use of resources, to mitigate natural hazards, and to better understand an environment under global change. Geosciences are well placed to provide answers to emerging questions through innovative fundamental and applied research. Current changes can be placed within the time-space continuum of Earth's evolution, allowing predictions for the future, using state-of-the-art mechanistic understanding of the processes involved.

Predicting how the Earth system will react to short and long-term impacts will help our society face the challenges ahead of us, adapting and mitigating the changes. Each subsystem has its own scientific challenges, but they interact on varying timescales with each other.

Society most directly interacts with the atmosphere and the near-surface environment. Atmospheric and environmental sciences thus have established and developed sophisticated, accurate, permanent long-term monitoring sites and mobile measurement equipment to determine trends, variability and transient or sudden changes of environmental and atmospheric variables, which can be monitored over human timescales. Many of these changes are reported at long-term in-situ measurement sites and they occur on short (annual) or long (decades or longer) timescales and are the result of both natural changes and human interaction. Because it provides the metrological basis for Earth observation, space geodesy has been an international endeavor to realize a hierarchy of highly accurate and stable terrestrial reference frames and timing on global, regional and local scales. The necessary infrastructure consists of large global networks of fundamental stations comprising large very long baseline interferometry (VLBI) and satellite laser ranging (SLR) telescopes and thousands of global navigation satellite system (GNSS) stations. Switzerland has a central role in understanding and monitoring climate and environmental changes due to its location in the Alps.

An ever-increasing population leads to an increased exposure of society to geohazards, requiring improved understanding of the coupling among the geospheres and the biosphere, which modulate environmental changes. Movements within Earth were ultimately responsible for mountain building, interacting with the forces shaping the near surface, surface and atmosphere. Extreme meteorological conditions such as large and sudden precipitation events or rising temperatures (fast thawing permafrost) influence the near surface conditions leading to latent slope failure. Even a moderate earthquake could be the trigger for a disaster, such as Alpine lake mudflows and debris flows. Rapid and flexible deployment of instruments will respond to immediate needs and allow the further development and test of new ideas about geoscience processes acting in different geospheres. It is hence crucial to foster fundamental and applied research in all geospheres. The geosciences are developing and applying state-of-the-art analytical methods to read the rock record and to determine the rates of change and transformation of fossil and active systems on Earth. This is only possible with large-scale facilities (as discussed in Pillar III) and costly drilling campaigns (IODP, Box 1; ICDP, Box 2).

Modern geosciences produce both physical and digital geo-referenced data in increasing volumes. Access to these data needs to be simplified, to provide science, society, industry, and governmental agencies with opportunities to make use of the generated knowledge. Appropriate curation of geoscientific data is crucial for streamlining geoscientific research and ensuring its reproducibility. Geoscientific data comprise all data resulting from geoscientific sampling, monitoring, processing, analysis, as well as stored physical samples or even digitized historic data, including their associated metadata. The exact geo-referencing of digital data requires a sophisticated data management system to facilitate access, dissemination and analysis and physical samples necessitate a modern facility to ensure ideal storage conditions in long-term archives and adequate analytical core logging and subsampling capacities functioning as a centralized physical data hub. These facilities in turn require well-trained and permanently employed technicians and data scientists.

Hurricane Dorian Seen From Aboard the Space Station
(photo: NASA)

7 Main Scientific Questions and Challenges in Geosciences

Geosciences have become increasingly aware of the fact that Earth functions as an integrated system, in which energy and materials are cycled between the different geospheres and the biosphere. The adjoining geospheres can serve as boundary conditions for geosphere-specific questions. Hence, the feedback among geospheres needs to be tackled explicitly. This chapter provides an overview of the current issues and questions relevant for the Swiss geosciences that should be addressed with adequate research infrastructures and activities. Many questions are geosphere-specific. But most importantly, an integrative whole-system approach is needed that links several geospheres instead of separating them into subdomains. We thus proceed through the geospheres from the top (atmosphere) down to the center of solid Earth (lithosphere), and synthesize in the final part of the chapter, how current questions can be linked across all geospheres and the biosphere.

7.1 The Links Among Different Geospheres

Many of today's key scientific questions and challenges in Earth systems science are related to the impact of anthropogenically driven land-use and climate change on the environment from local to global scales. Global change triggers shifts in elemental and molecular fluxes among the geospheres. Many of these changes have important consequences for the sustainability of human-natural systems, yet they remain poorly understood and quantified. Both land-use and climate are currently undergoing rapid changes at rates that are unprecedented in human history. Documenting and understanding these profound environmental changes in a perpetual, quantitative and comprehensive fashion is therefore of paramount importance for environmental resource sustainability policies. Building upon the available information from historical data, such an approach will also allow a) documenting environmental changes and detecting tipping points and thresholds prior to the onset of significant system impacts, b) defining the baseline and amplitudes of natural/non-anthropogenic environmental changes, and c) providing an early warning system for unexpected changes as well as more accurate predictions.

In this context, the atmosphere is an important component of an integrated, whole-system view of the Earth system, and thus we group the current key topics into four groups, focusing on 1) the effects that extreme deviations from the average climate exert; 2) changes in atmospheric composition and environmental pollution (air, water, soil, waste deposits, etc.); 3) impacts on the critical zone [2] where the hydrological cycle interacts with the Earth surface, and 4) the Alpine landscape.

7.1.1 From Climate Change to Climate Extremes

In Switzerland, the effects of climate change are often perceived only via increased average temperatures, whereas the magnitude and frequency of extreme events are underestimated or ignored. In reality, not only sea-level rise, but also increasing frequency and severity of extreme events (more severe and more frequent soil and atmospheric droughts, heat waves, wildfires, floods and storms) is the most likely outcome that goes beyond increased mean temperatures and shifting precipitation patterns. Hence, we use the term 'climate extremes' to address extreme short-term to multi-year deviations from the climatic norm. However, our knowledge about the capacity of Swiss ecosystems that are typically less exposed to extreme dry conditions and high temperatures (> 25 °C) to respond to more intense and more frequent climate extremes remains limited. Understanding ecosystem response to climatic extremes requires long-term, high-quality data on ecosystem functioning, in particular on growth, nutrient cycling, and CO_2, water, and energy fluxes. The Swiss forests monitoring framework (Boxes 3, 4, 5) and the LéXPLORE lake platform (Box 6) is a first step in this direction. However, the current setup is insufficient to comprehensively capture forest response to climate (or weather) extremes on a larger (national) scale in a statistically representative way. This can be achieved only by a dense long-term monitoring network capturing all components of the critical zone.

IODP's Chikyu scientific drilling vessel operated by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The D/V Chikyu is currently the world's most advanced scientific drilling vessel, capable of drilling deeper below the seafloor than any other science drilling vessel to date. (photo: JAMSTEC/IODP)

BOX 1: IODP

IODP, the international Ocean Discovery Program is an international research program that aims at unraveling Earth's history and dynamics using ocean-going scientific drilling vessels that allow recovering and investigating sub-seafloor sediments and rocks as well as long-term monitoring of seismicity, subsurface fluid chemistry, biogeochemical cycles, and microbiology. The IODP focuses on scientific drilling projects investigating a) climate and ocean changes through sedimentary archives; b) biosphere frontiers through studies of deep life, biodiversity, and environmental forcing of ecosystems; c) deep Earth processes and their impacts on Earth's surface environments; and d), dynamic processes and geologic hazards that also occur on human time scales.

http://www.iodp.org

ICDP's Deep Lake Drilling System (DLDS), a barge and drill rig combination to recover unconsolidated sediment and hard rock cores from deep lake bottoms. The system is capable of recovering core from up to 1,400 m depth. Shown here is the DLDS in action on Lake Towuti (2° S, 121° E), Indonesia, anchored at a water depth of 150 m recovering 175 m of sediment core and the underlying bedrock. (photo: Marina Morlock)

BOX 2: ICDP

ICDP, the International Continental Scientific Drilling Program, is the terrestrial counterpart of IODP (Box 1). ICDP aims at generating the most precise fundamental and globally significant knowledge on the structure, composition and processes of Earth's crust, through the unique capabilities of continental scientific drilling. ICDP is organized by an international consortium, provides infrastructure for scientific drilling on Earth's continents including their continental shelves investigating sites of global significance and socioeconomic relevance. ICDP projects retrieve the otherwise inaccessible rock record of tectonic, climatic, and biological cycles from the present day back into deep time. Drilling projects in particular address four key themes: a) **geodynamic processes**, such as the initiation of plate tectonics and the evolution of crust and mantle; b) **geohazards**, such as earthquakes and volcanoes; c) **georesources**, including low-carbon energy technologies as well as water, mineral and metal resources; and d) **environmental change** addressing paleoclimate and paleoenvironment all the way back to the Archean, subsurface biosphere and hominid dispersals and its connection to the environment.

https://www.icdp-online.org

7.1.2 Atmospheric Chemistry and Environmental Pollution

Changes in atmospheric composition, e.g., through the anthropogenic emissions of trace gases and aerosols, constitute key drivers of climate change. However, other spheres are also closely involved. For example, the carbon cycle is the focus of much current research; yet some of the key areas of investigation, such as the potential for soil carbon sequestration or the rates at which increased chemical weathering can offset anthropogenic carbon emissions, remain in their infancy due to the lack of a long-term, coordinated research agenda. The same holds true for the nitrogen cycle, with atmospheric nitrogen dry and wet deposition affecting biodiversity and vulnerable ecosystems – and is a source of the potent greenhouse gas nitrous oxide.

Other atmospheric components such as aerosols and chlorofluorocarbons also have a strong impact on climate. The UV-blocking stratospheric ozone layer with its seasonal minimum in the Arctic and Antarctic still has not recovered entirely, despite undisputed successes of measures taken under the guidance of the 1987 Montreal protocol. In addition, the impact of air pollution in combination with other environmental pollutions on ecosystems and human health remains a concern.

Furthermore, the adverse effects of environmental pollution on human health, e.g., due to elevated atmospheric concentrations of aerosols, tropospheric ozone, carbon monoxide and nitrous oxides, and their impact on ecosystems such as acidification of lakes, rivers and forests due to excessive inputs of sulfur and nitrogen remain a concern. Excess nutrient deposition and exposure to ozone can harm crops and adversely impact ecosystems.

7.1.3 The Critical Zone

The critical zone is Earth's permeable near-surface layer, from the top of the trees to the bottom of the groundwater.[2] In this zone, the hydrological cycle and its perturbations are widely recognized as pressing environmental issues owing to changes in cloud and precipitation patterns and groundwater extraction, glacier retreat, and reorganization of atmospheric circulations systems. The interactions between water and different biogeochemical cycles, are largely uncharted due to the difficulty of simultaneously accounting for changes in several biogeochemical cycles. Yet understanding the ways in which biogeochemical cycles interact over space and time and the effects on/from human activities, is critical to our ability to decipher and predict the future evolution of emerging properties such as water quality, soil fertility and greenhouse gas fluxes, to name a few. Soils are particularly important as they are a non-renewable resource of great ecological and economic value. They fulfill many functions and provide services of vital importance to society. However, current management of the critical zone is not sustainable. Changes in nutrient cycles and climate challenge soil health. The soil is being degraded by the activities of construction, erosion, compaction and pollution. The main research questions relating to the critical zone focus on soil threats and how to combat them, and on soil responses to a changing environment.

Soil ecosystem services need to be protected and strengthened to reach the UN Sustainable Development Goals (SDGs). Threats such as soil erosion, soil pollution or loss of fertility due to human activities are still poorly understood and should be more intensively studied in order to prevent natural hazards and maintain healthy ecosystems and healthy populations. Furthermore, soil ecosystem services, as defined by the UN FAO, such as water purification and reduction of contaminants, climate regulation (e.g., by storing more C in soils or reducing nitrous oxide emissions), nutrient cycling, biodiversity, flood regulation and of course provision of food, fiber and fuel urgently need to be promoted.

7.1.4 The Alpine Landscape

Besides the process-oriented view of the critical zone, a regional view on the Alpine region of Switzerland and neighboring countries is of the highest importance in this rapidly changing world. This region is already subjected to significant changes in the future; such as the melting of glaciers, the thawing of permafrost, the increasing risk of natural hazards, and the decrease of biodiversity and associated ecosystem services. It is further under pressure from the effects of new constructions for tourism and renewable energy exploitation, as well as the effects of demographic and socioeconomic changes. Hence, these changes are not only due to the changing climate. The Alpine region not only serves as an Alpine laboratory for studying the effects of local to global changes and for developing sustainable environmental policies, but it should also be an example for many mountainous regions around the globe that are facing similar challenges.

Investigation of the impact of drought and drought release on Carbon allocation at the long-term irrigation experiment Pfynwald, in a 100-y-old naturally regenerated Scots pine (*Pinus sylvestris* L.) forest. Measurement towers provide access to the top of the canopy and hold sensors for meteorological and phenological long-term measurements inside and above the forest canopy to investigate element fluxes and cycles in a drought prone forest ecosystem under global change. (photo: Marcus Schaub, WSL)

BOX 3: LWF

The Long-Term Forest Ecosystem Research Infrastructure (LWF RI) consists of 19 permanent monitoring sites on which up to 30 parameters have been continuously measured since 1994. It is part of the Europewide ICP Forests (Box 4) network. The intensive monitoring plots (Level II) are being complemented by 50 forest health monitoring plots (Level I), providing long-term data series since 1985. The combination of both data sets allows an advanced understanding of air pollution and climate change effects on Swiss forest ecosystems, in terms of process- and system understanding as well as model validation (ground truthing of remote sensing approaches). LWF aims for early detection of changes in forest condition, risk assessment for anthropogenic and natural stress scenarios. Since 2019 and in collaboration with eLTER, the Swiss Long-Term Forest Monitoring plots are on the European Roadmap for Research Infrastructure (ESFRI).

https://www.wsl.ch/lwf

Long-term measurements of litter, heavy metal, stemflow, meteorology, and radial growth by means of dendrometer tapes at the ICP Forests plot 'Solling Beech', Germany. The regularly managed plot is intensively monitored since 1968. The crucial environmental factors being measured are nitrogen and acid deposition that reach the Solling summit originating from the surrounding lowlands. (photo: Stefan Fleck, ICO-Forest)

BOX 4: ICP Forests

The International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) was launched in 1985 under the Convention on Long-range Transboundary Air Pollution (Air Convention, formerly CLRTAP) of the United Nations Economic Commission for Europe (UNECE). ICP Forests monitors forest condition in Europe at two monitoring intensity levels: The Level I monitoring RI is based on ca. 5,852 observation plots on a systematic transnational grid of 16 × 16 km throughout Europe to gain insight into the geographic and temporal variations in forest condition. The Level II intensive monitoring RI comprises ca. 623 plots in selected forest ecosystems with the aim to clarify cause-effect relationships. At present, 42 European countries are participating in the program, which includes assessments according to harmonized and standardized methods. The publicly available long-term data series from ICP Forests provide the scientific basis for political decisions on air pollution control and thus contribute to the elaboration and review of protocols of the CLRTAP.

http://icp-forests.net

7.2 Probing the Near-surface and Deep Earth

Between the large field scale and the small laboratory scale approaches there is a major spatial gap. The main progress in recent years was made by reducing the spatial and temporal scales in field studies through temporary, focused deployments of measurement equipment, leading to understanding in seismic rupture propagation, seasonality in deformation patterns, interaction with the hydro- and cryosphere and high-resolution imaging of Earth's interior. Exciting advances are within reach, but they require spatially and temporally denser sampling of our environment. Targeted deployments will provide critical data for understanding, for example, the nucleation of geohazards. An improvement in resolution of geophysical and geodetic observation stations will bring the analysis scale closer to the human scale and consequently the laboratory scale, which should allow better understanding and modelling of processes, as well as their interactions with the other geospheres.

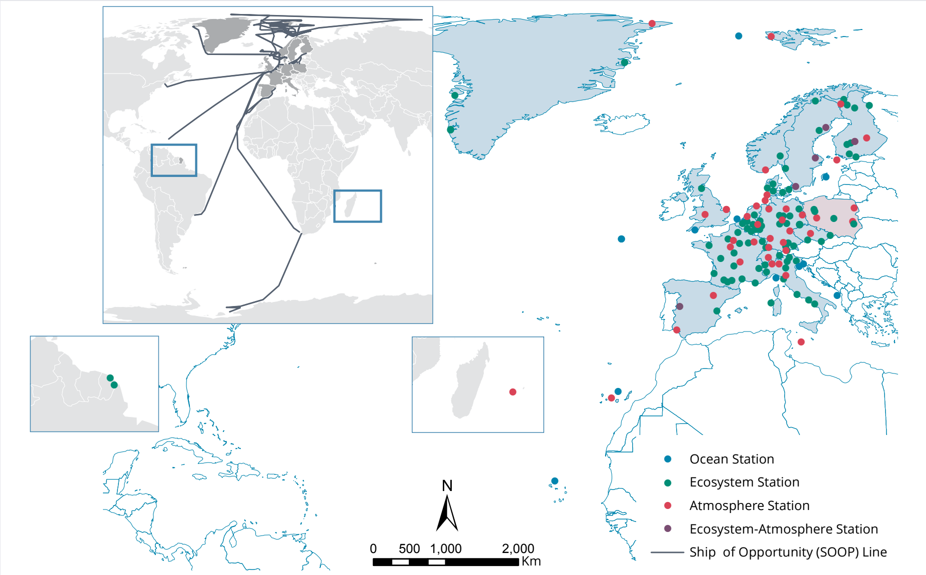
Currently there is a re-thinking of deep Earth geosphere processes, which are traditionally considered to evolve slowly, over millions of years, but lead to rapid releases of energy that provoke punctuated rapid events, such as volcanic eruptions and earthquakes. Advances in analytical and modelling approaches have shown that a better way to understand the mechanisms is to see the long-term evolution of the Earth as a sequence of innumerable short, yet variable-speed, events that add up to provide an understanding of the overall, billion years long evolution of the Earth. Hence, a key theme for Earth and environmental sciences is to improve understanding of timescales and rates of change in deep time, leading to a better understanding of the interactions between the deep Earth, and the other geospheres. Hot topics include the current attempts to improve mechanistic models of fluids interacting with geomaterials in shallow and deep processes. Enclosing waste (e.g., carbon and nuclear waste storage) in natural rock formations, as well as extracting heat in geothermal reservoirs, requires a profound understanding of rock-fluids interaction from the sub-nanometer scale of mineral surfaces to 100's of kilometers on the mountain scale. These timescales and rates are fundamental to understanding complex processes such as mountain building and the contributions of deep Earth element cycles (such as carbon, nitrogen, sulfur and water) to the other geospheres. Successful understanding of the data requires adapting physical and chemical models on the atomic scale to the Earth sciences, and extensive coupling to large scale and ultimately to Earth-scale modelling. Ground truthing requires openly available, large, high quality data structures that have been designed for data mining. This way, observational and analytical data can be used together with a theoretical framework to model and predict the behavior of long-term carbon capture and storage, geohazards such as tsunami formation, landslides and volcanic eruption and the feedbacks of deep-Earth processes on climate and the biosphere.

Additionally, probing Earth through scientific coring and drilling activities is crucial to understand rates and processes at geological time scale. Having access to infrastructure and drilling/coring platforms that provide long-term records and archives is necessary to understand 1) the effects of climate change, tipping points and extreme events on Earth's surface and its link to all the other spheres, 2) the link between the deep biosphere, environmental forcing of ecosystems and the geospheres, 3) the impact of Deep Earth processes on Earth's surface environments, 4) the relation between dynamic processes (earthquakes, seismicity) and geologic hazards at human timescales. Having appropriate physical access to sub-surface sediments and rocks, as well as long-term monitoring of subsurface fluid chemistry, biogeochemical cycles and microbiology should therefore remain an important goal of the Swiss Geosciences Community.

7.3 Towards Integrative Earth System Science

Each geosphere has its own questions and approaches, as outlined above. Each of the spheres is well established in Switzerland, and the scientific outcomes from research in Switzerland in each discipline are highly advanced and visible. Hence, the currently successful disciplinary research needs to be further strengthened and complemented by integrative, interdisciplinary research. This is increasingly necessary to better understand the interactions along the boundaries of the individual geospheres, which is often facilitated by scientists' needs to jointly use large research infrastructures (e.g., ACTRIS, eLTER, EPOS, GAW, ICDP, ICOS, IODP, SwissOGS). There are many feedbacks from one geosphere onto the adjacent ones, and these need to be nurtured by adequate large-scale infrastructure programs and facilities. The four pillars for large infrastructures proposed in this roadmap embody this realization. Steps towards integrative Earth system sciences are proposed that build upon and integrate the many separate and distributed instruments and sensor networks. The challenge is to combine all the types of existing and new observations and data into one overarching multi-disciplinary observation system, the Integrated Swiss Geosciences roof that is supported by four strong infrastructure pillars in Fig. 1.

Scientific advancements also depend on cyberinfrastructure to analyze, process and store large datasets. Ultimately, diverse data types from Earth sciences and other disciplines need to be integrated. There is however, a high diversity and dimensionality of data regarding thematic content (e.g., geological maps, profiles, geochemical data), but also spatial coverage, temporal referencing, resolutions, scales, homogeneity, and the associated, not always generally applicable, data models, types and formats (e.g., vector, raster, voxel, xyz, single/multi parameter measurements). Specifically, physical data (e.g., unique samples of geo-materials, such as cores) pose complex challenges related to the different types of sample materials that require long-term storage and curation. Such a storage facility is an indispensable requirement to meet obligations and standards imposed by international conventions and funding agencies. Furthermore, data may originate from different projects, programs, institutions, and individual researchers, but also from different measurement methods, protocols, sensors and analytical processing methods, and different requirements for data transfer speeds. For many research projects, a combination of newly acquired and existing data from different domains is essential in order to carry out (multi- and interdisciplinary) analytical work. Nevertheless, researchers often spend a large part of their time and money on searching, accessing, preparing and analyzing these datasets because an integrated framework for all geoscientific data within a common reference frame and easy-to-use interfaces is entirely missing in Switzerland. Another obstacle to overcome is the dispersion of the data over various data owners with individual access models, and who often also show some reluctance to share data with e.g., scientific competitors. Thus, open data with an open-access policy and adherence to the FAIR principles [1] must become the standard, and restrictions become limited to few well justified cases.



Map of the ICOS station network in 2020.
(image credit: ICOS ERIC)

BOX 5: ICOS

The Integrated Carbon Observation System Research Infrastructure (ICOS RI) (https://www.icos-ri.eu) integrates atmosphere, ecosystem and ocean greenhouse gas observations to provide data for research, policy making, and the general public. ICOS RI brings together European research communities and measurement stations and constitutes a Europe-wide research infrastructure that serves both scientists and society. Swiss contributions are made through the ICOS-CH consortium running ICOS projects at the stations Jungfraujoch (Atmosphere) and Davos (Ecosystem).

ICOS-RI is coordinated by the legal entity of ICOS ERIC (European Research Infrastructure Consortium). ICOS ERIC was established by the European Commission on 23 November 2015. ICOS was also recognized as European Landmark Infrastructure in 2016 in recognition of its scientific excellence and of competitiveness within the European Research Area. ICOS – CH has been and continues to be part of the Swiss Roadmaps for Research Infrastructures 2013–2016, 2017–2020 and 2021–2025. The Swiss National Science Foundation classified ICOS as a 'RI of major importance'.

https://www.icos-cp.eu
https://www.icos-switzerland.ch

BOX 6: LéXPLORE

The LéXPLORE platform consists of a 10 × 10 m^2 floating pontoon equipped with high-technology instrumentation and a closed laboratory with permanent direct and safe lake water access for scientists. LéXPLORE, installed on Lake Geneva, is protected against fishing nets and navigation by a 70 m radius zone for scientific purposes. The overarching goal is to foster collaborative and interdisciplinary studies focusing on the biosphere including freshwaters and atmospheric systems. The LéXPLORE platform delivers high-quality data through a newly developed open access data infrastructure following the FAIR principles. The LéXPLORE is a joint infrastructure of five institutes and universities (Eawag, EPFL, UNIL, UniGE and Carrtel) and is open to all scientists.

https://lexplore.info, https://www.datalakes-eawag.ch

View of the LéXPLORE platform, a floating laboratory installed in Lake Geneva since 2019. (photo: Damien Bouffard)

Rolling though the Appalachians
(photo: NASA)

8 The Present Swiss Landscape: Major Successes and International Context

The current roadmap for the years 2025–2028 is the first geosciences-specific roadmap that was developed in Switzerland. Hence, evaluation of a previous roadmap is not possible at this time. Nevertheless, significant developments in infrastructures occurred during the period 2017–2020. These were based on initiatives of individuals or groups of researchers, universities, or other stakeholders.

Geosciences research in Switzerland is well organized in general, and has an excellent international reputation. We are excited by the opportunity provided by the deliberation leading to the roadmap, as it has opened up an exciting future for geosciences, in which more interdisciplinary research can be promoted with new opportunities to train the next generation of geoscientists.

8.1 The Atmosphere

A whole suite of existing, upcoming and new national and international RIs is listed in the latest Swiss Roadmap for Research Infrastructures in view of the 2021–2024 SERI Dispatch[3] (hereafter: SRfRI). In the SRfRI, the following geosciences RIs were mentioned: 1) the Integrated Carbon Observation System Research Infrastructure (ICOS RI; Box 5); 2) the Aerosols, Clouds and Trace gases Research Infrastructure (ACTRIS RI; Box 7); 3) the Airborne Research Facility for the Earth System (ARES; Box 8); and 4) the integrated European Long-Term Ecosystem, critical zone and socio-ecological Research Infrastructure (eLTER; Box 9). These RIs are at different stages in terms of maturity, spatial and temporal coverage and extent: ICOS became operational in November 2015 (establishment of the ICOS European Research Infrastructure Consortium, ICOS ERIC); ACTRIS was adopted on the European (ESFRI) roadmap in 2016 and is currently in the implementation phase (passed the ERIC step 1 process and applied for step 2 in early 2021); and eLTER was adopted on the ESFRI roadmap in 2018. The SRfRI includes ICOS, ACTRIS and eLTER as infrastructures in which Swiss institutions already participate, and the SERI-Dispatch (2021–2024) lists them as research infrastructures that should be funded, together with ARES that is listed as 'fundable RI'.

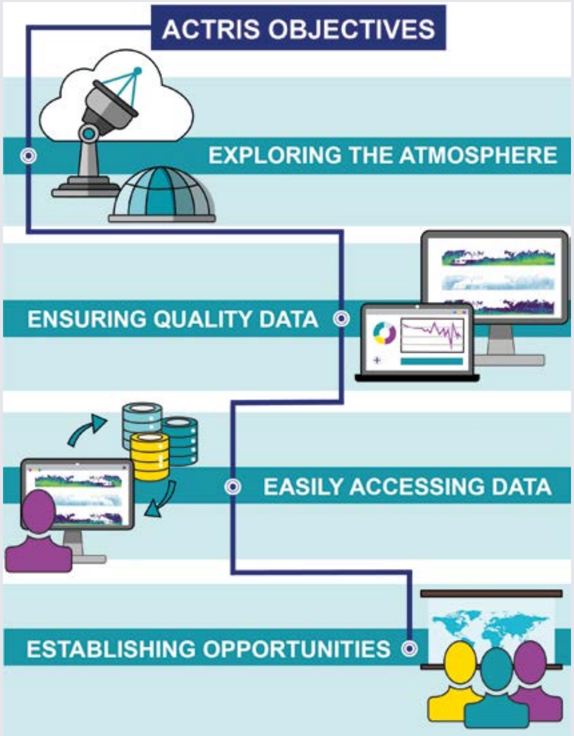
In Switzerland, ICOS (focusing on climate-relevant greenhouse gases) and ACTRIS (focusing on aerosols and trace gases relevant for air pollution) complement each other and share common infrastructure at the Jungfraujoch High Altitude Research Station (HFSJG; Box 10) which is one of the most renowned atmospheric monitoring stations in the world. The importance of long-term measurements in the atmosphere for individual campaigns with specific research goals is best demonstrated by the long-term measurements of aerosol particle size distribution being instrumental for the interpretation of data obtained in a transnational access activity of the European Union.[4]

Besides their strong international character, ICOS, ACTRIS and eLTER are also of importance on the national scale as they attract scientific collaborations that link and integrate national activities with international programs to harmonize protocols and ensure compatibility among observations.

While the two ICOS stations HFSJG (Atmosphere; ICOS, ACTRIS) and Davos (Ecosystem; ICOS, LWF, ICP Forests and eLTER) are well embedded in the European networks of more than 130 monitoring stations located in up to 16 European countries, the Swiss urban site in Basel is planned to be upgraded and incorporated in the ICOS network during the next phase. Similarly, Switzerland plans to contribute to ACTRIS with the activities at the monitoring stations HFSJG, Payerne and Beromünster. Moreover, three different atmospheric simulation chambers operated by the Paul Scherrer Institute are part of a cluster of simulation chambers (EUROCHAMP[5]) which are eligible for transnational access to promote international collaboration.

Quantification of greenhouse gas emissions is an urgent issue that can only be tackled with direct flux measurements at the atmosphere – biosphere interface. Ecosystem-scale CO_2 and H_2O flux measurements based on the eddy covariance method are operational at seven long-term sites of the Swiss FluxNet (Box 11). With its unique collection of data, Swiss FluxNet has played a major role in advancing our understanding of the contribution of the Swiss ecosystems to greenhouse gas emissions under different climatic conditions and land management intensities. However, although forests cover 30% of Switzerland, they remain underrepresented with only two sites, one at Davos and the other at Laegeren. A representation of forests particularly at the dry end of the Swiss climate space is currently lacking in the national and global flux network.

The Swiss Optical Ground Station and Geodynamics Observatory at Zimmerwald (SwissOGS; Box 12) was established in the late 1950s to conduct optical as well as Satellite Laser Ranging (SLR) observations. Since then, it



ACTRIS: A Research Infrastructure to ensure the provision of easily accessible long-term and high-quality, data of aerosol, clouds and trace gases in the atmosphere. (image credit: ACTRIS Head office)

BOX 7: ACTRIS

ACTRIS-RI (Aerosols, Clouds and Trace gases Research Infrastructure) (https://www.actris.eu) is a pan-European initiative to consolidate permanent and long-term observations of aerosols, clouds and trace gases at distributed National Facilities. In situ measurements are complemented by remote sensing activities to address important environmental and societal challenges such as air quality, adverse health impacts or climate change. In Switzerland, the Jungfraujoch, Payerne and Beromünster will be contributing to ACTRIS. These observation sites are complemented by the Atmospheric Simulation chambers at PSI, as an Exploratory Platform within ACTRIS. With these sites, Switzerland will further enhance its key role in ground-based atmospheric observations in Europe.
ACTRIS was adopted on the ESFRI roadmap in 2016, and it is planned to form an ERIC (European Research Infrastructure Consortium). ACTRIS shall be fully operational in 2025. ACTRIS-CH is part of the Swiss Roadmap for Research Infrastructures 2021–2024.

http://www.actris.eu

JPL and UZH personnel at Dubendorf airbase in front of the AVIRIS-NG imaging spectrometer built into a Super KingAir. (photo: ARES)

BOX 8: ARES

The Airborne Research Facility for the Earth System (ARES) is an integrated research infrastructure to measure terrestrial processes of the Earth system at regional scale. The core of ARES is a next-generation imaging spectrometer operating in the solar-reflective domain (400-2500nm), built jointly with NASA JPL. Data from complementary remote sensing instruments are assimilated in models within a dedicated computing infrastructure. The tight integration of state-of-the-art sensors with sophisticated models through a computing infrastructure will be unique within Switzerland and Europe, delivering world-class data and science output to the Earth System Science community, fostered by a FAIR (findable, accessible, interoperable, and reusable) infrastructure with an open access data policy. ARES will be available primarily for Swiss researchers who are collecting data in Switzerland. As an open platform, it will also be made available to researchers on an international level to optimize the system usage through deployments outside Switzerland. ARES is part of the Swiss Roadmap for Research Infrastructures 2021–2024.

https://ares-observatory.ch

has been continuously extended, e.g., for Global Navigation Satellite System (GNSS) observations, and improved with emerging cutting-edge technology. SwissOGS is part of a global network of international fundamental geodetic stations under the Global Geodetic Reference Frame (GGRF), today's basis for all georeferencing and Earth observation, with Zimmerwald being the reference point for all surveying and mapping in Switzerland. The Automated GNSS networks for Switzerland AGNES[6] and Coupled Seismogenic Geohazards in Alpine Regions (COGEAR)[7] have been collecting data for more than two decades. These permanent multi-purpose GNSS networks not only provide reference stations for geoscientific applications, but also contribute significantly to geophysics and geodynamics as well as atmospheric research in Switzerland. They thus provide a solid link between the upper and the lower spheres.

8.2 The Biosphere, the Interface Between Geospheres

The interface between the atmosphere and the solid Earth, also known as the 'critical zone'[2] is a key component of geoscientific research and provides a strong link between the geosciences and the biosciences, including biodiversity research. In biodiversity, major and rapid species redistribution, range reduction and loss, community reshuffling, and degradation and disappearance of unique habitats have occurred worldwide. Long-term RI and monitoring programs were set-up in many countries to provide critical data for quantifying, understanding and predicting such changes and their impacts, and for informing environmental policies. Relevant monitoring programs partially or entirely focusing on mountain biodiversity and ecosystems include the Swiss Long-Term Ecological Network, the Global Observation Research Initiative in Alpine Environments (GLORIA), the Permanent.Plot.ch project, the Swiss National Forest Inventory, as well as specific sites in particular in the Alps of Canton de Vaud and Valais. Yet in Switzerland, existing biodiversity RI and monitoring programs tend to inadequately represent mountains, even though they are among the greatest ecosystem service providers and biodiversity sanctuaries.[8]

The Long-Term Ecological Research in Europe (eLTER) network capitalizes on research infrastructures such as the in-situ network of sites and information technology. The increasing complexity of ecosystem research led to the networking and the establishment of the European eLTER and the global iLTER organizations, supported by two major, complementary Horizon 2020 projects and incorporated into an overarching Dynamic Ecological Information Management System-Site and Dataset Registry (DEIMS-SDR[9]).

Monitoring of ecosystems is a central activity within the UNECE Convention on Long-range Transboundary Air Pollution (1979)[10], the oldest international, multilateral environmental agreement. The establishment of ICP Forests (Box 4) (and LWF; Box 3, in Switzerland as a part of it) as a measure implemented by this convention is a success story, with monitoring of forest ecosystem promoting and documenting the effect of environmental policy on physical, chemical and biological components of the ecosystems. One major success is the drastic reduction of SO_2, NOx and NH_3 in Switzerland and Europe since the 1980s. At present, the ICP Forests long-term observation RI is the only monitoring network that is able to assess the inter-annual and decadal trends of forest vitality and mortality as affected by climate change and air pollution.

In collaboration with eLTER, the Swiss Long-Term Forest Research (LWF; Box 3) plots are included in the ESFRI Roadmap since 2018. The LWF plots complement both the TreeNet (Box 13) and Swiss FluxNet forest sites, including the Davos class 1 ICOS and the Swiss FluxNet Laegeren sites.

8.3 Probing the Near-surface and Deep Earth

Swiss participation in the domains of solid Earth research has been continuously active for over a decade, as well as in recent years, within the framework of the European Plate Observing System (EPOS; Box 14). The tradition of geological and geophysical, targeted discovery campaigns abroad goes back for many more decades, with prominent successes, however those efforts were primarily institute- or group-driven. A key element of the successes was the early and strong link to natural laboratories like the Alps at our doorstep, and to analogous systems around the globe, as well as that many fundamental discoveries have been made by researchers in our country. Most of these conditions remain valid nowadays, but the increasingly widespread use of mobile instrumentation by other countries opened a stiff competition in which Switzerland must keep up the speed and its position in the leading group.

Switzerland plays a very prominent role in satellite and space geodesy in Europe and globally. SwissOGS is performing as the second-best Satellite Laser Ranging stations world-wide and is one of the very few global observatories for space debris tracking with optical methods. University of Berne, ETH Zurich, EPFL and swisstopo have been and are contributing significantly to the Global Geodetic Observing System (GGOS), a huge global infrastructure for Earth system monitoring, encompassing all the important space geodetic techniques and their global networks of stations. Switzerland also contributes significantly to the use of GNSS for high-precision applications in many interdisciplinary fields ranging from positioning, timing, global and regional reference frames to water vapor and ionosphere monitoring, and early warning systems for natural hazards. As an important international activity in geodesy, Switzerland is leading a large consortium of European and global institutions in the field of global gravity field determination and combination (COST-G)[11]. Similarly, the seismological observatory has a long tradition in high-quality local and global detections and cooperations (see Nuclear Non-Proliferation Treaty), and research institutions are active in exploring the Earth's crust at various scales and purposes around the world, with a particular emphasis on mountain belts.

In the Earth sciences, the last decade has seen an increased effort to reduce redundancies by increased collaboration between the actors (swissuniversities) promoting research. Such collaborations are now well established among the rock physics laboratories which are quite well distributed across the country like the Mont Terri, Grimsel and Bedretto underground rock laboratories. The Integrated Ocean Drilling Program (IODP; Box 1) and the International Continental Scientific Drilling Program (ICDP; Box 2) related research activities are coordinated under the umbrella of www.swissdrilling.ch (Box 15) for example. Over the past years, researchers from Swiss institutions have actively been involved in scientific drilling initiatives by engaging in various IODP and ICDP projects. A number of these drilling projects have been initiated and developed by Swiss research consortia, highlighting Switzerland's leading role in scientific drilling. Moreover, Swiss scientists are taking an active role in envisioning and formulating the future IODP and ICDP integrated science plans, as well as shaping EPOS. Based on the long-term past funding commitment, the community counts on forthcoming commitments on a project basis for the 2025–2028 funding period, allowing Switzerland to continue to be a reliable and trusted partner in these endeavors. It furthermore provides the basis to continue the outstanding research in the Earth sciences and attractiveness of our institutions, as well as the over-proportional engagement in planning and developing its long-term strategy.

The Swiss Secondary-Ion Mass Spectrometry Facility (SwissSIMS)[12] is a first step in the direction of facilities proposed here. It was created to offer state-of-the-art geochemical instrumentation for analyzing a large range of isotopes and trace elements in solid materials. All partners would benefit from a coordinated effort to operate large-scale infrastructures and use them together with the existing ones in a science-driven governance that promotes access for all stakeholders (universities, ETH-domain, federal agencies, and industry).

eLTER site Zöbelboden, Austria. Zöbelboden was established in 1992 as the only Integrated Monitoring station in Austria under the UN Convention on Long-Range Transboundary Air Pollution (CLRTAP). In 2006 it became part of LTER Austria. The Zöbelboden represents one of the best-known karst catchments in Europe with long-term data series of the major components of its ecosystems. In the picture you can see meteorological and air pollution measurements. (photo: Umweltbundesamt Austria, F. Rokop)

BOX 9: eLTER

The emerging European Long-Term Ecosystem, critical zone and socio-ecological systems Research Infrastructure (eLTER RI) is a pan-European Research Infrastructure planned to be operational by 2027. It is based on existing networks and ecosystem, critical zone and socio-ecological research projects from 162 organizations in 19 countries, making use of 35 selected sites and platforms in terrestrial, freshwater and coastal ecosystems, combined with observational data from additional 50 sites. The objective of eLTER is to expand research capacities by engaging current and new users and fostering cross- and transdisciplinary research. Progress in understanding, managing and securing ecosystem functions and services is challenged by fragmented and dispersed ecosystem research, which prevents a holistic understanding of complex eco- and socio-ecological systems. The eLTER RI was evaluated by the European Strategy Forum on Research Infrastructures (ESFRI) as having high potential for closing this gap in the European RI landscape.
https://www.lter-europe.net

Aerial view of the Sphinx Observatory at Jungfraujoch with the Aletsch Glacier in the background. (photo: http://www.jungfrau.ch)

BOX 10: HFSJG

The International Foundation for the High Altitude Research Stations Jungfraujoch and Gornergrat (HFSJG) dates back to 1930. Member countries are Austria, Belgium, China, Finland, Germany, Great Britain, and Switzerland. Its purpose is to provide infrastructure and support for scientific research of international significance that must be carried out at an altitude of 3000–3500 meters above sea level or for which a high Alpine environment is required. Jungfraujoch, at an altitude of 3450 meters, is the highest research station in Europe that is accessible all year round by public transportation. Jungfraujoch is embedded in many national and international programs and networks such as the Detection of Atmospheric Composition Change (NDACC), Global Atmosphere Watch (GAW) program of the World Meteorological Organization (WMO)[63], Class 1 station in ICOS and a site within ACTRIS. Cooperation among Alpine infrastructures is lively through the Virtual Alpine Observatory (VAO).
Its sister station, Gornergrat is located at 3135 meters above sea level, and is mainly known for the two astronomical observatories, but its infrastructure is also used for investigations in cryosphere research, e.g., glaciology and permafrost.

https://www.hfsjg.ch,
https://www.icos-cp.eu

Many of the Swiss universities and the ETH-domain have done very well in global rankings in the geosciences in the last three years, reflecting the excellent quality of both education and research. Switzerland has always had a strong tradition in geosciences, with natural laboratories like the Alps at our doorstep, and many fundamental discoveries have been made by researchers in our country.

The Swiss geosciences community has been particularly efficient in developing and maintaining geochemical facilities. Switzerland is among the leading nations in interdisciplinary interactions between geosciences and other disciplines by sharing knowledge and facilities that are dedicated to determine timescales and rates of Earth and environmental processes such as the facilities at the Universities of Bern, Geneva, Lausanne, and at ETH Zurich, which were and are involved in key techniques such as Rb/Sr, K/Ar and Ar/Ar dating, U/Th/Pb dating, cosmogenic nuclides dating and thermoluminescence dating; the geoanalytical platforms using different types of mass spectrometry (e.g., ICP-MS and TIMS) at several universities across Switzerland, including some globally unique instruments such as the Tom Dooley gas spectrometers at ETH Zurich, and the cryo-NanoSIMS at UNIL/EPFL. Despite such strengths, the geochemical landscape is rather fragmented and would strongly benefit from a coordinated effort.

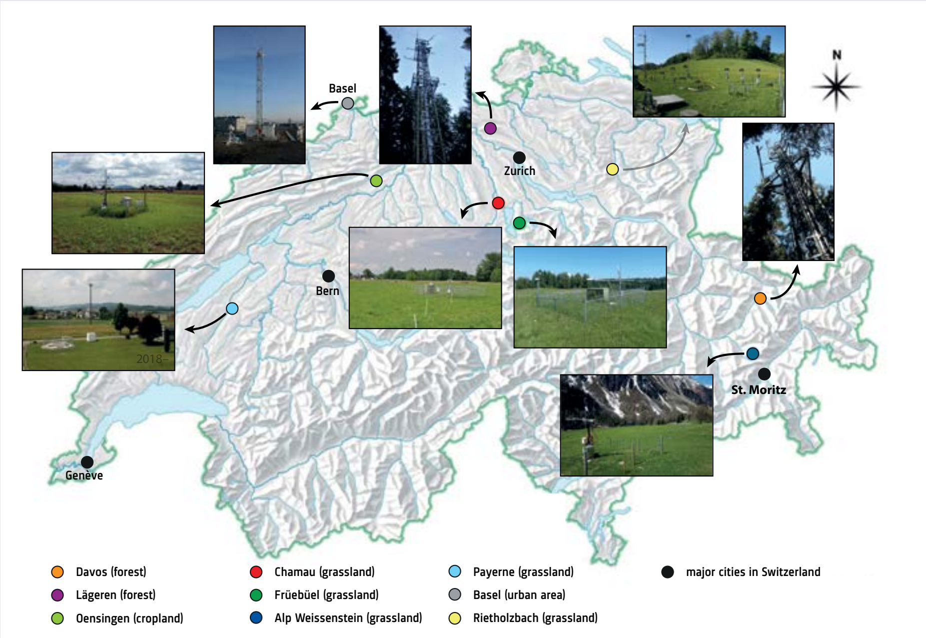
8.4 Data Infrastructure: Interdisciplinary Open Data Collection

Within the last years, several measures have been implemented to facilitate efficient research data management and analysis in Switzerland. SWITCH[13] proposes a so-called Connectome[14] which references and links research data in distributed repositories for common use, and SWITCHengines[15] provides computing and storage services in the form of virtual machines. The Swiss National Supercomputing Center (CSCS) offers high performance computing services and large storage capacities for scientific purposes and the Swiss Data Science Center (SDSC)[16] provides support and an infrastructure for data science within the ETH-domain[17]. The University of Geneva offers the Yareta Portal[18] for archiving and preserving research data in the long term, which ultimately should lead to a national solution through the OLOS[19] project.

Platforms such as the Swiss Data Cube (SDC; Box 16), the Airborne Research Facility for the Earth System (ARES) and the Data Reception and Archive at the University of Bern[20] have been established to simplify the way of accessing and processing satellite imagery. Consulting and data search services are provided by the National Point of Contact (NPOC)[21]. Regarding remote sensing data, it is important to be integrated into the international context and thus to be well connected with organizations such as the Committee on Earth Observation Satellites (CEOS)[22], including GEOSS[23]. However, access to some satellite imagery sources is limited because Switzerland does not participate in the respective programs, such as Copernicus.[24]

Other Swiss domain-specific infrastructures, often with international ties, exist in the form of the Glacier Monitoring Switzerland (GLAMOS)[25] network, the World Glacier Monitoring Service (WGMS)[26], the Swiss Permafrost Monitoring Network (PERMOS)[27], the Swiss Seismological Service (SED)[28], the Georesources Switzerland Group (FGS)[29] and the Geology Portal[30]. Notable initiatives in the environmental sciences include Biodiversity Monitoring Switzerland[31], the Centre Suisse de la Cartographie de la Faune (CSCF)[32] and the National Forest Inventory (NFI). The GeoVITE platform[33], provided to scientific institutions by ETH Zurich, allows for intuitive, seamless browsing, extracting, and downloading of original public authority and scientific base map data.

Apart from these (often non-publicly available) research-centric endeavors, there are a considerable number of cantonal and federal data infrastructures. One of the most important ones is the Federal Spatial Data Infrastructure (Bundes-Geodaten-Infrastruktur FSDI)[34], which was initiated as a consequence of the ('Federal Act on Geoinformation') of 2009[35] and which has links to international organizations such as INSPIRE[36], UN-GGIM[37] and OGC[38]. The FSDI is most prominently 'materialized' in the map. geo.admin.ch[39] geoportal, provided by swisstopo. Another very laudable tool by swisstopo is geocat.ch[40], a metadata service, referencing a large number of geodatasets provided by public authorities, agencies, and companies. In line with Open Government Data[41], the Federal Digital Switzerland Strategy[42], the Swiss Federal strategy for geographical information[43], swisstopo basic geodata will be free from March 1, 2021[44].Data of the Swiss National Air Pollution Monitoring Network (NABEL) are publicly available the Federal Office for the Environment's webpage.[45]



The Swiss FluxNet initiative combines ecosystem-scale CO_2 and H_2O vapour (at some sites also CH_4 and N_2O) eddy-covariance flux measurement sites in Switzerland. It currently encompasses seven long-term ecosystem sites, covering the major land-use types in Switzerland: forest, cropland, and grassland. By the end of 2020, 105 site-years were available for all sites. (image credit: Werner Eugster, ETHZ)

BOX 11: Swiss FluxNet

Swiss FluxNet is a network of seven long-term ecosystem greenhouse gas flux measurement sites, covering major land-use types in Switzerland (grassland, cropland, forest, urban). Over the years, the network has acquired enough funding to expand in size and scope and currently six of the sites are run by the Grassland Sciences group at ETH Zurich. By the end of 2020 the network provided 105 site-years of CO_2 and H_2O vapor fluxes. The network includes one of the longest running arable flux sites globally (Oensingen, since Dec. 2003), the 8th oldest flux site globally (Davos, since January 1997), and one of the longest running urban sites (Basel). The Davos site was labelled as an ICOS Class 1 ecosystem research station in November 2019. In recent years measurements of CH_4 and N_2O fluxes were added to one grassland, one coniferous forest, and one cropland site. At all sites, complementary measurements, e.g., validating net carbon budgets, solar-induced fluorescence, as well as experiments, are conducted to address critical research questions (e.g., effect of drought and land management on ecosystem functioning).

http://www.swissfluxnet.ch

With the advanced requirement to document and store digital data as required by SNSF, there is also a push for storage of unique physical samples. Many sampling and measurement campaigns result in precious sample sets, which cannot be obtained again without a large effort. Examples are the Swiss participation in international programs such as IODP and ICDP (Box 1 and 2) or Eurofleets[46]. Also, the cryospheric community would benefit greatly from a refrigerated storage capacity for drill cores (frozen), not only for pure ice cores, but also for frozen lithospheric cores taken from permafrost regions. A modern long-term storage facility for physical data (geo-samples, e.g., cores, rock samples) is required. This should complement established approaches, such as the Swiss Natural History Collections Network (SwissCollNet/SwissBioColl)[47], which aims at unifying physical and virtual access to biodiversity and geodiversity information.

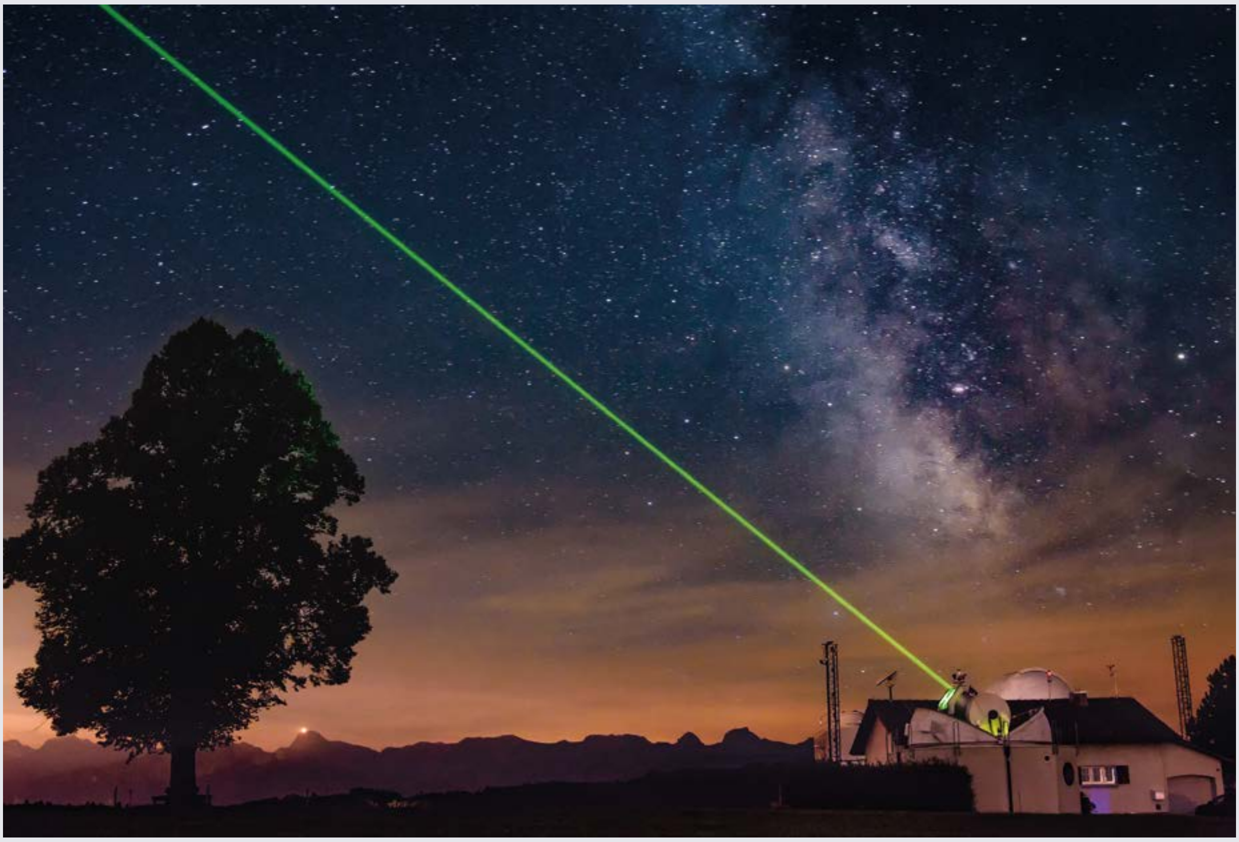
Virtual and physical data curation is regarded as being even more important in the light of the new Open Research Data[48] policy of the Swiss National Science Foundation (SNSF)[49]. Similarly, swissuniversities[50] has been mandated to set up a national strategy on open access and open research data[51] with different stakeholders in Switzerland. Hence, fair access to data can only be guaranteed by a Swiss-wide facility.

Although Switzerland has established a considerable number of data infrastructures and services, there is no integrated platform on the federal level suitable for the current and future needs of geoscienfic data management. Inspiration for the implementation of such an infrastructure can be drawn from other international efforts, such as the EarthCube[52] platform, which is part of the larger US-based Cyberinfrastructure for the Geosciences[53], the National Geological and Geophysical Data Preservation Program[54], the European Distributed System of Scientific Collections (DiSSCo)[55], the Environmental Data Initiative[56], EUDAT[57], the Research Data Alliance[58] and the European Open Science Cloud[59]. Establishing such a national Swiss data infrastructure for the geosciences would allow the Swiss research community to more closely collaborate and exchange data with scientists around the world. Thus, the proposed infrastructure would play a pivotal role in strengthening international collaborations and partnerships promoting interdisciplinary and multidisciplinary research at the forefront of the Geosciences.

8.5 Participation in International Research Infrastructures

Participation in international Research Infrastructures (RIs) also offers possibilities in joining consortia for European Commission’s Horizon 2020 calls specific for European research infrastructures. As an example, ETH Zurich, Empa and University of Bern are currently participating in a Horizon 2020 project called RINGO (Readiness of ICOS for Necessities of integrated Global Observations)[60] which was submitted to the H2020-INFRADEV call which was open only to existing RIs. The recently started ACTRIS implementation project (ACTRIS-IMP) with participation of PSI and Empa is also funded through the H2020-INFRADEV call. Switzerland supports the Global Atmosphere Watch (GAW)[61] Precision Filter Radiometer (PFR) network for aerosol monitoring through the Physics and Meteorology Observatory Davos/World Radiation Center (PMOD/WRC)[62] and under the supervision of the World Meteorological Organization (WMO)[63] with its headquarters in Geneva, Switzerland. ETH Zurich successfully participated in three EC projects (FP7/H2020) directed at the build-up of EPOS (Box 14).

The major effort to build a pan-Alpine consortium to run the AlpArray[64] program and its seismic network with over 600 sensors brought other lessons for the future. The coordination of research and the coordinated use of so many, sometimes very large, mobile equipment pools did not fit any European funding scheme; therefore, national funds were gathered with an extra effort to make a coherent schedule. This was a major challenge, and long-term operation was not granted. While some of the sites remained occupied on a permanent bases, others were abandoned to put instruments into follow-up, large network projects, designed in the footsteps of AlpArray.

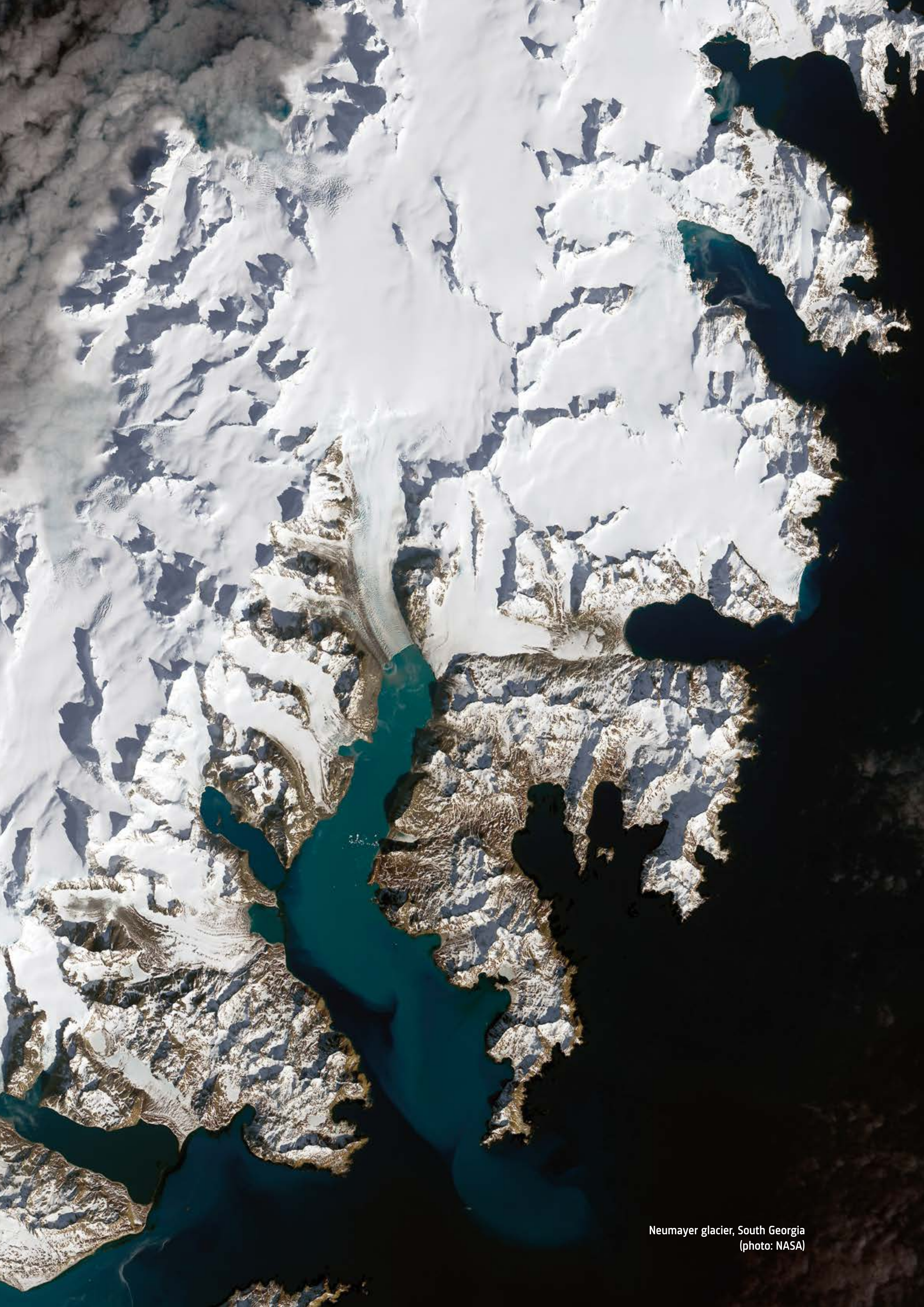


Laser beam transmitted from the 1-meter ZIMLAT telescope at the SwissOGS to measure the distances of artificial satellites with a mm-accuracy. (photo: AIUB, Emiliano Cordelli)

BOX 12: SwissOGS

The Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald (SwissOGS) is a station of the global tracking network of the International Laser Ranging Service (ILRS). Satellite Laser Ranging (SLR) observations to dedicated satellites equipped with laser retro-reflectors are acquired 24 hours a day and 7 days per week with the monostatic 1-m multi-purpose Zimmerwald Laser and Astrometry Telescope (ZIMLAT). SLR at SwissOGS contributes to the determination of the International Terrestrial Reference Frame (ITRF), especially to the origin and scale, precise orbit determination, and the determination of the long-wavelength part of the Earth's gravity field. All these efforts have to be seen in the larger context of the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG), where SwissOGS is the most productive SLR station in the northern hemisphere, to advance our understanding of the dynamic Earth system by quantifying our planet's changes in space and time.

https://www.aiub.unibe.ch/forschung/observatorium_zimmerwald/index_ger.html



Neumayer glacier, South Georgia
(photo: NASA)

9 Synergies with Other Scientific Fields

Synergies between the geosciences and other scientific fields have slowly evolved over time. Historically, the geosciences focused strongly on geology and associated disciplines dealing with the abiotic solid Earth components. Increasing interest and collaboration amongst the life and environmental system sciences began, first with paleontological research, which aimed to link bones and fragments found in sedimentary rocks with living organisms of the present time, and to deduce the form, shape and ecosystem-related role of fossil organisms in their geologic era. This required the extension of geoscientific research towards hydrology, the biosphere and the atmosphere, to depict the climate of geologic eras, and how it is related to the organisms that lived during the past. At present, the deep biosphere and the hydrosphere under climate change – two emerging fields during the last two decades – remain an underexplored, poorly understood, yet pivotal part of the global biosphere. Tailored scientific drilling allows geomicrobiologists to characterize and quantify this 'hidden' biomass and to investigate its role in altering biogeochemical cycles and the rock record through consumption and production of solutes and mineral phases. Detailed genetic methods furthermore allow identifying community composition and metabolic potential. In addition, drilling projects are ideal platforms to address the past, present, and future Earth system, typically adopting a modern interdisciplinary approach through the combination of several key disciplines in the broad field of natural sciences. Notwithstanding, the societal aspects, as described below, depend upon drilling knowledge, bridging the gap between Earth and social science.

A direct link between geosciences and human well-being and health is found in relation to pollutants, climate-relevant greenhouse gases, and ecosystem services such as biodiversity, providing ecosystem services to humans. Pollutants often originate from fossil fuel burning or solid Earth erosion, affecting public health directly via inhalation, and indirectly via drinking water, ecological problems and contaminated soils.

In this context, Geo-OBSERVE (Pillar I, Chapter 11) and Geo-MOBILE (Pillar II, Chapter 11) would allow many synergies between geosciences and bio- as well as social sciences, especially in the fields of atmosphere – pedosphere – hydrosphere – biosphere exchange, biodiversity, ecosystem services, and ecosystem management. Geosciences also serve as immediate sensors of anthropogenic effects on the environment, as demonstrated recently by the global quieting of seismic noise due to COVID-19 pandemic lockdown measures[65]. Finally, geosciences research and related players also carry the responsibility to inform policy makers, the public, and to educate next generations on how the Earth works and evolves, on its own and in interaction with humankind.

Hence, detailed spatial and temporal observations of (bio-)geochemical fluxes and rates of change will provide information on the impact of anthropogenic and environmental factors that determine ecosystem functioning. Detailed and spatially highly-resolved measurements of greenhouse gas fluxes from soils and water bodies can be integrated with large-scale measurements of these gases in the atmosphere as performed in the field of atmospheric chemistry and physics. This will help to provide unprecedented detailed understanding of fluxes and processes across the different spheres and will enable source attribution of atmospheric trace gases and aerosols. The proposed Geo-OBSERVE research infrastructure will also allow for spatially highly resolved detection of the accumulation of pollutants, toxins, and pharmaceuticals, and their transport, thereby providing links to the fields of environmental chemistry and medicine/health.

These modelling and measurement efforts go hand in hand with an ever increasing amount of geoscientific data. As a consequence, concepts to efficiently make sense of these data from domains such as data science and artificial intelligence are expected to become an important part of geoscientific research in the future, necessitating collaboration with research groups from these fields.

By providing the metrological basis and terrestrial as well as celestial reference frames for all observation on the Earth and in space, space geodesy establishes links to disciplines far beyond the geosciences, namely to astronomy, planetology, fundamental physics, and metrology.

In general, it can be stated that synergies with other scientific fields are numerous in geosciences, as it is located at the crossroads between many different topics, and uses tools developed by other science domains to understand our planet. As a clear testimony to these synergies, many of the Earth science departments have subsections in geophysics, geochemistry, geobiology, geoengineering, and more. Developing new fields such as environmental mineralogy (nano particles), astrobiology, and others will be crucial to remain at the forefront of geoscientific research.

With respect to the 2025–2028 roadmaps, the geosciences aim for an integrated geosciences infrastructure, while biology aims for an integration of existing, distributed infrastructures by complementing them with a central, highly equipped hub at one of the existing sites. Strong synergies between both, the roadmap for geosciences research and the roadmap of research infrastructures in biology will take place under pillar I and IV, in the Integrated Long-term Observatory, drilling programs and digital and physical data storage and curation. Common sites will be established to complement existing sites in the two distinct networks of highly equipped sites proposed in the two roadmaps to facilitate collaboration and allow more synergies and exchange between these two fields.

BOX 13: TreeNet

TreeNet is the biological drought and growth indicator network that collects continuous and high-resolution data on soil water content and stem radius fluctuations measured with point dendrometers on more than 350 trees at 35 forest sites all over Switzerland. These data are the basis for near-real-time information on tree growth and tree water deficit to better understand the soil-plant-atmosphere system. The water related physiological processes are the result of the dynamic imbalance between water loss (transpiration) and water uptake by the roots. The network is supported by WSL, ETH Zurich and IAP and complements the LWF and SwissFluxNet.

https://treenet.info

TreeNet is an international monitoring and research network in which automated tree stem radius fluctuations measured with point dendrometers (see picture) are analyzed in terms of forest ecosystem responses to climate change. Continuously measured data of microclimate and tree physiology provide real-time information on tree water relations and tree growth. (photo: Roman Zweifel, WSL)

10 Relationship to Federal Agencies, Industry and Education

Federal Agencies

Ever since sustainability of the environment has gained public awareness, the geosciences have played a key role for many federal and industrial stakeholders. The proposed infrastructures will strengthen the interaction with federal agencies, and provide solid support for policy makers. Geosciences are charged with the study of the Earth as a whole and, as such, are involved in assuring the availability of resources, monitoring the environment and assessing impacts of society on the Earth system by using both human-scale observations as well as the billion-year history of Earth. Switzerland is uniquely placed at the crossroads of climate impact on resources such as water, the effects of extreme weather events on natural hazards in mountainous environments, as well as the inherent risks associated with an active mountain range. As such, geosciences provide much of the data and understanding needed for decision making processes of governmental agencies. Key federal agencies in close contact with the geosciences are the Federal Office for the Environment (FOEN)[66], the Federal Office of Meteorology and Climatology[67], the Federal Office of Topography[68], which includes the Swiss Geological Survey, the Federal Office of Spatial Development (ARE)[69] and the Federal Statistical Office (FSO/BFS)[70]. The importance of this close collaboration is demonstrated by a large number of directly supported services and programs in geosciences, such as the Swiss Seismological Service (SED), the Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald (SwissOGS; Box 12), the permanent multi-purpose GNSS network AGNES, the Global Climate Observing System GCOS[71], the National Air Pollution Monitoring Network NABEL[72], the Swiss Soil Monitoring Network (NABO)[73] and the newly funded competence center for soils (KOBO)[74], linking Federal Offices for the Environment, for Agriculture and for Spatial Development.

Industry

Geoscientific research interacts with industry in many aspects, providing deep knowledge, basic concepts, data, and highly trained collaborators, as is manifested by numerous spin-off companies and close collaborations between industry and academia. Ground truthing and development of state-of-the-art instrumentation can be done at the ICOS, ACTRIS, ICP Forests, eLTER, LWF and PMOD/WRC sites for atmospheric monitoring. In geosciences, innovative observation and measurement principles have been developed which are then licensed to companies producing commercial instruments or leading to start-ups and spin-offs (e.g., IRsweep, Miro Analytical Technologies, Leica Geosystems Heerbrugg, u-blox, Saphyrion and Astrocast, Geoprävent, Geoazimuth, Fix Position and Astrocast, Esri Inc.). These interactions span the atmospheric domain, geodesy, environment, but also the geochemistry and solid Earth domain.

Unlike in other countries, there has not been a big emphasis on metallic resources and fossil fuel extraction, but geoscientists have provided and will continue to provide the necessary know-how to industry for the exploitation of non-metallic resources (gravel, sand limestone), and increasingly, water and renewable energy exploitation. There is great interest in understanding the subsurface amongst other for the planning and realization of large transportation infrastructures, for waste disposal (e.g., radioactive waste, NAGRA[75], Mont Terri[76]; CO_2 sequestration) and for the management of low and high-enthalpy geothermal exploration, which are currently at applied science stages (Bedretto Laboratories[77], and many others). Switzerland also plays a leading role in monitoring and remediation of polluted soils in Europe, namely in the field of soil remediation (shooting ranges, petrol stations industry, etc.).

Education and Society

Educating Bachelors, Masters, and Ph.D. students, the population at large, as well as providing experts with forefront knowledge in the geosciences, equips Swiss society with the necessary know-how to deal with the challenges associated with the ever increasing population density on our planet and the impacts of climate change. The societal pressure on resources, energy and environment has become enormous and will continue to further increase, which requires an integrated approach to geosciences and a new generation of smart Earth scientists to help tackle the increasingly complex tasks of the future.

One of the most important contributions to Swiss industry are human resources, which are capable of transferring state-of-the-art knowledge, for example experience from international collaborative IODP & ICDP drilling projects, to applications such as deep wells used for geothermal energy and waste disposal. Fundamental research results are applied in the evaluation of geological hazards such as landslides, rockfalls, lake tsunamis, inundations, and avalanches, which play an increasingly important role due to crowding of the planet and climate change. Finally, insurance companies need better constraints on rates and impacts of the different kinds of geo-hazards that threaten our country, including earthquake hazards.

Highly trained specialists are formed through participation in international and national programs (M.Sc. and Ph.D. programs and doctoral schools at Swiss universities and ETH-domain). Swiss universities are highly ranked internationally, and highly visible geosciences programs are offered by the ETH-domain institutions at Lausanne and Zurich, as well as the universities of Basel, Bern, Fribourg, Geneva, Lausanne, Neuchâtel, and Zurich. Various short courses and summer schools address topical aspects of geosciences, and are extensively used by Swiss and international students and early career scientists.

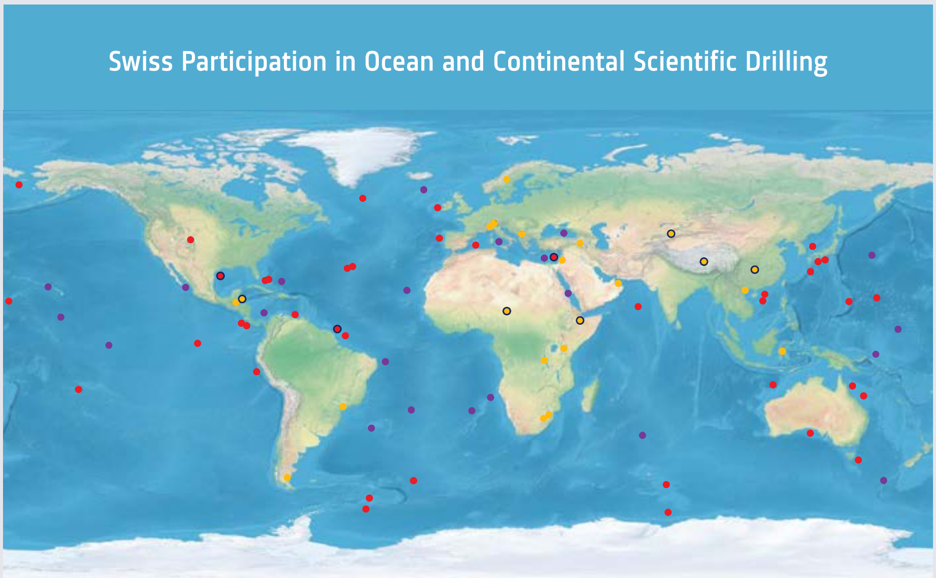
Swiss scientists and institutions are heavily involved in public outreach. An example of public outreach includes the LWF Test-, Training- and Demonstration plot[78], where WSL, in collaboration with the MINT learning Center at ETH Zurich[79] is offering school students the opportunity to experience forest research 'in the real world'. Students can use real measuring installations, sample collectors and data to formulate research questions, experiment and discuss results within the LWF Test-, Training- and Demonstration plot and the WSL Tree-Ring Lab[80], or the Earthquake simulation laboratory at ETH Zurich[79] capable of simulating the effect of earthquakes on people. Finally, an emerging field in outreach is the citizen science approach, using low-cost devices or simple observation protocols at a large number of geographically distributed localities that help geoscientists to compile a geographically explicit picture of geoscientific processes, e.g., in the field of earth quake hazards. In Switzerland, GLOBE Switzerland[81] is directly interacting with interested geoscientists in the field of phenological observations[82]. A successful example of international outreach was the installation of low-cost seismometers in Nepali schools to 1) do basic seismological observations and earthquake monitoring and 2) to develop an educational program to increase awareness and preparedness levels[83], which received great international attention.

EPOS, the European Plate Observing System, is the Eurpean Research Infrastructure for Solid Earth Sciences. (photo: Barbara Angioni, INGV EPOS 2021)

BOX 14: EPOS

EPOS, the European Plate Observing System, is the unique European Research Infrastructure for solid Earth sciences. Established as European Research Infrastructure Consortium (ERIC) in November 2018, and presently in its pilot operational phase, EPOS integrates and coordinates the existing national and transnational solid Earth science research infrastructures and datacenters in ten thematic domains ranging from geology, seismology, volcanology, geomagnetism, … to experimental laboratories, anthropogenic hazards and GeoEnergy Testbeds (i.e., underground labs). Within EPOS, data from tens of thousands of sensors across a broad range of geophysical phenomena, together with derived products and associated services, are being made available through a harmonized and interoperable e-infrastructure, fostering and supporting innovative and multi-disciplinary solid Earth science research.

https://www.epos-eu.org

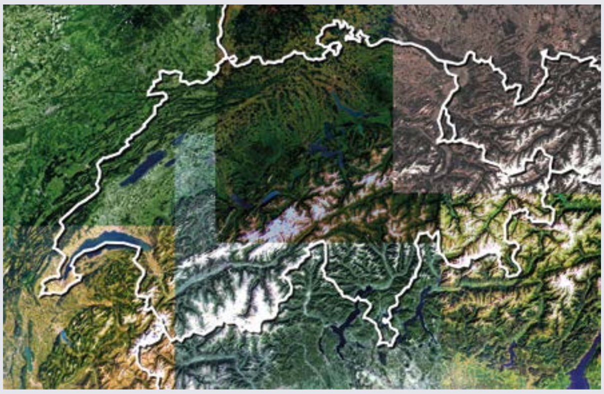


World map showing past and current Swiss participation and leadership in international ocean and continental scientific drilling programs since 1968 (IODP) and 2008 (ICDP), respectively. Yellow circles = ICDP drilling sites with Swiss participation; yellow circles with black outline = upcoming ICDP expeditions with Swiss participation (2020 onwards); red circles = ODP & IODP expeditions with Swiss participation (1983–2020); red circles with black outline = upcoming IODP expeditions withSwiss participation (2020 onwards); violet circles = DSDP expeditions with Swiss participation (1968–1983).
(image: Miriam Andres, UniBe)

BOX 15: Swissdrilling.ch

SwissDrilling.ch is the central platform coordinating Switzerland's participation in international scientific drilling. SwissDrilling provides the central hub as key link and liaison for Swiss-based scientists to the two scientific drilling programs IODP and ICDP. Funded by the SNSF, SwissDrilling has become an integral part of the Swiss Geosciences landscape, by actively fostering a Swiss scientific drilling community through communication (including its webpage), regular meetings, presence at the Swiss Geoscience Meeting with a booth and dedicated sessions. SwissDrilling further helps with proposal planning, enquiries and handles financial reimbursements. It further serves as Switzerland's link to the European Consortium for Ocean Research Drilling (ECORD) in terms of communication and outreach.

http://www.swissdrilling.ch



The SwissDataCube project provides centralized access to heterogeneous earth observation data. (photo: Geodata swisstopo, administrative boundaries EuroGeographics)

BOX 16: Swiss Data Cube (SDC)

The main objective of the Swiss Data Cube (SDC) is to support the Swiss government for environmental monitoring and reporting. It enables Swiss scientific institutions to facilitate new insights and research and to improve the knowledge on the Swiss environment using environmental observation (EO) data. The information potential of EO data has not yet been fully exploited. They still remain underutilized mainly because of their complexity, increasing volume, and the lack of efficient processing capabilities. SDC lowers the barriers caused by these Big data challenges and provides access to large spatio-temporal data in an analysis ready form.

https://www.swissdatacube.org

Snow and Sand in Central Asia
(photo: NASA)

11 Vision for the Future and its Implementation: The Integrative Geosciences Infrastructure

11.1 Pillar I — Integrated Long-Term Observatory

Switzerland is a key player in several international research programs that strive to understand the Earth as an integrated dynamic system. To get beyond past achievements, our vision is to establish a new Integrated Long-term Observatory (Geo-OBSERVE; Fig. 1) research infrastructure for the geosciences on the foundation established by the successful tradition of geoscientific long-term observations. The goal is to benefit from decade-long observations that are key to understand how different components of the Earth system respond to changing forces and how they interact with each other through coupled feedback mechanisms. **Our vision is to establish and strengthen collaborations between the existing disciplinary observation networks: to intensify, strengthen and substantially expand ongoing and recent activities in combination with establishing new sensor networks for the observation of emerging key variables of the Earth system to address the most urgent geoscientific and associated societal questions (Fig. 2).** Improving the collaborations among individual players and integrating the various disciplines in a whole-system approach is the only way to solve some of the big challenges, such as long-term global change impacts on ecosystem services in the future.

Long-term and multi-scale observations are a key research target in Earth sciences across various temporal and spatial scales. The longer the records, the more we learn about important, but faint trends that are barely detectable in noisy time series, temporal variability, and transient processes. Similarly, despite recent developments, there is still a gap in the spatial coverage between various approaches and ground truthing. Hence, it is a fundamental prerequisite to intensify the investigation of the factors and processes that make our planet habitable, and to define the path toward the sustainable use of Earth's resources. The Swiss geosciences community has expressed the need for observatories capable of capturing the impact of ongoing global change on the environment at a spatial and temporal resolution that is thus far unprecedented. Owing to the tremendous impact of global change on all Swiss Alpine geospheres and biosphere, a detailed characterization of the rates and scales of change is necessary to inform policy makers in developing mitigation strategies.

In addition, there is a large gap in knowledge on the effects of future climate conditions on ecosystem structure and functioning. Observational networks and models do not provide sufficient information on how ecosystems react to interactions among environmental drivers (e.g., soil drought, atmospheric drought, flooding, temperature, CO_2). To understand such interactive effects, climate change and environmental observatories in representative ecosystems (agricultural land, forests, grasslands, etc.) in Switzerland should be established and integrated within Geo-OBSERVE. The Geo-OBSERVE concept should also include the urban dimension, as the main source of anthropogenic greenhouse gasses and pollutant emissions. Switzerland-wide, as well as a site-specific (catchment-size) long-term observations of gas flux, soil and aquatic chemistry, forest growth, plant and faunal diversity, tree water deficit, hydrology, water vapor, but also displacement and mass movement as well as long-term experimental research platforms with manipulated drought (Pfynwald[84]), CO_2 (Davos Stillberg[85]), flooding, and temperature should be further established and fostered. Furthermore, rural and remote stations should cover primary and secondary air pollutants such as aerosols and trace gases.

The realization of the Geo-OBSERVE will play an essential role for the transfer of information, data and expertise across disciplines. The Geo-OBSERVE plans to build on existing research infrastructures and to integrate specific monitoring and experimental sites (ACTRIS, ARES, AGNES, COGEAR, eLTER, EPOS, GAW, GCW, HFSJG, ICOS, ICP Forest, LWF, SwissOGS) which will require continued financial support. Of equal importance is continued participation in large infrastructures to which Switzerland has access via continuing membership (namely IODP and ICDP).

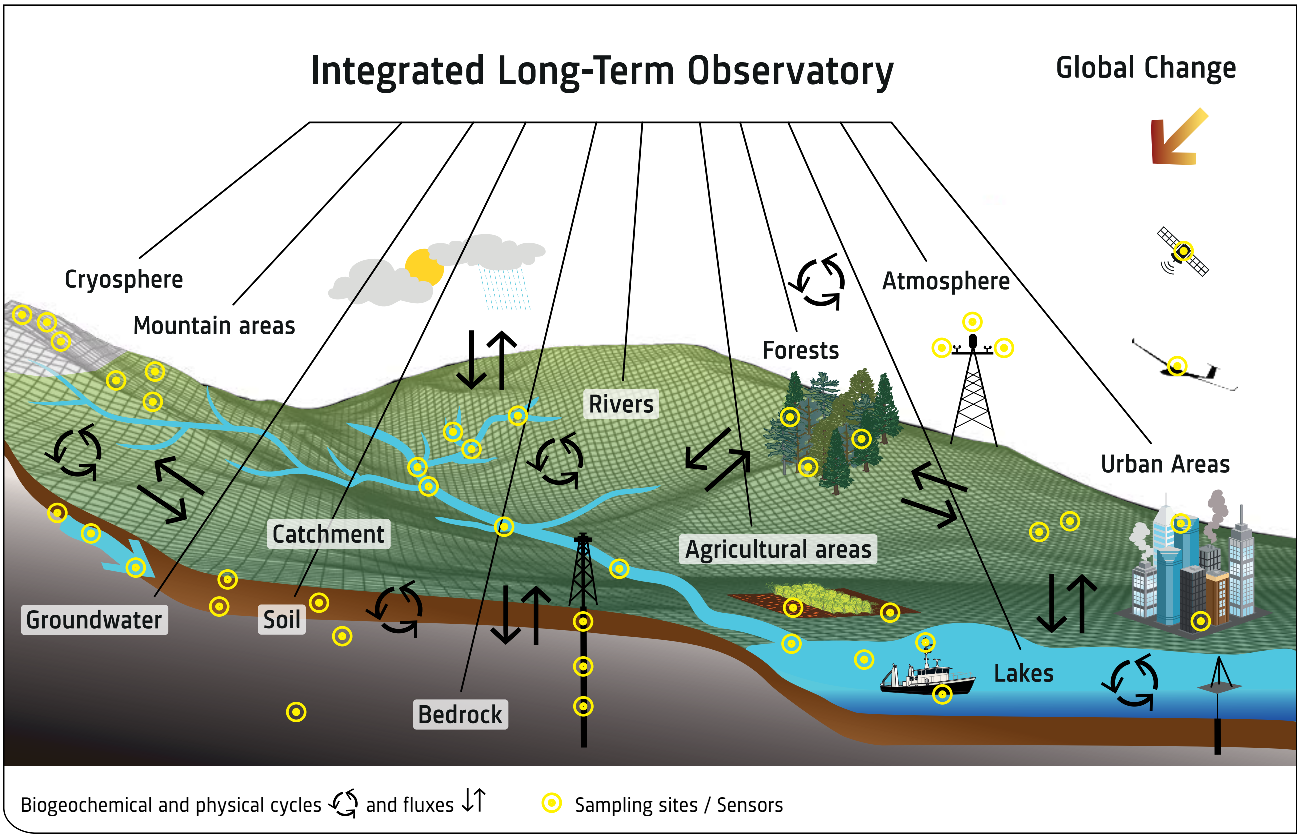


Fig. 2: The Integrated Long-Term Observatory will combine highly equipped observatories and sensor networks to unravel the cycles and fluxes of water, carbon, nutrients, aerosols and trace elements across all spheres. (image credits: The trees, crops, urban area and research vessels are vector illustrations by Jane Hawkey, Ian Image Library, https://ian.umces.edu/imagelibrary; background: Dmitriy Razinkov)

The vision of Geo-OBSERVE emphasizes scalability among its components. This is important to link the various scales of data observation. For example, if large infrastructures such as those used by the Airborne Research Facility for the Earth System, the geodata portals or the Swiss Data Cube that curates time series of remote sensing data are considered, they operate at a different scale compared to field-based sites for measuring gas fluxes.

The Geo-OBSERVE will strongly benefit from emerging measurement technologies and satellite missions in geodesy. In particular, the increasingly important Global Navigation Satellite Systems (GNSS) nowadays contributes to a vast variety of applications and disciplines. With a spatial densification of the AGNES network with geodetic-grade dual-frequency, GNSS receivers, it will be possible to improves the spatial and height resolution in mountainous areas, which will be key for understanding natural hazards and their associated risks.

Finally, a funding pool should be created to simplify access to all geoscientific research infrastructures and to enact the open access and open data policies that are of great benefit for the development of the geosciences. This should ensure the syntactic and semantic interoperability of data. Thus, the data can be made available to all researchers without geographic limits.

11.2 Pillar II — Mobile Monitoring Infrastructure

In addition to the Geo-OBSERVE (Pillar I), large improvements in the spatial and temporal resolution of observations at the local scale are only possible through temporary deployments of the planned Mobile Monitoring Infrastructure (Geo-MOBILE). This should consist of versatile, mobile, fast response solutions, which are required to provide the Swiss geosciences community with the equipment for geophysical, geodetic and geochemical analyses to acquire the necessary data on poorly and insufficiently characterized processes and related societal challenges such as: 1) earthquakes and seismic hazards, 2) volcanic eruptions, 3) mass movements (land- and rock-slides, avalanches), 4) glacial lake outburst floods, and 5) atmospheric processes and meteorological extreme events such as links between air pollution and precipitation, hydrological floods, heat and drought. This mobile infrastructure, consisting of expensive sensors for the highest-quality measurements in combination with massive deployments of less costly sensors, is necessary for Switzerland because processes leading to natural events, which can become catastrophic, are usually characterized by such small amplitude signals that they would elude the detection capability of the permanent Geo-OBSERVE. To this end, shared mobile pools with a large number of sensors are envisaged, ideally combined in multi-parameter setups that would allow for dedicated and flexible deployments. Mobile sensor platforms are also important for ecosystem observations, to increase the spatial coverage of information and to provide a link to satellite based remote sensing.

The primary aim of the Geo-MOBILE is to substantially increase the resolution capability of mobile geoscience deployments in space and in time. The key goal is to narrow the gap between the characteristic size of observations and elements governing the process of interest. While the Geo-OBSERVE provides the broad, stable reference, some Geo-MOBILE tools still need to be high-precision devices, but an increasing amount can be planned with moderate performance sensors at the benefit of their larger numbers.

This vision emphasizes large, shared pools of mobile instruments for the observation of above- and below-ground processes. A first pool should consist on the one hand of a large number of recently developed novel dualfrequency GNSS receivers and antennas for short-term and medium-term monitoring campaigns in specific areas of the Alps. This mobile sensor network will allow for: 1) a very detailed monitoring of the movements of glaciers, rock glaciers, and landslides, as well as vulnerable Alpine infrastructure like dams; 2) the use of innovative new methods like GNSS reflectometry to determine the water equivalent of snow cover, soil moisture, as well as heights of ice, snow and lake surfaces; 3) the high-resolution retrieval of the water vapor content above the sites and of the space weather in Switzerland, which is highly coupled with climate processes; and 4) a fast reaction to earthquakes via a task force (see below) is made possible in order to measure post-seismic displacements. A complementary part of the above-ground sensors should focus on bio-, cryo-, pedo- and hydrosphere monitoring tools, with the help of various field stations and portable labs for on-site chemical, physical and biological sample analyses, e.g., to respond to pollution episodes and to understand the immediate effects of contaminants on the soil, water and biota. On the other hand, an atmospheric mobile laboratory encompassing a range of in-situ and remote sensing instruments has enormous potential to contribute to a wide range of interdisciplinary science including meteorology, atmospheric aerosols, air quality, hydrology, biogeochemical cycling, greenhouse gases, and satellite validation (including ESA validation activities). The facility could provide infrastructure support at national and international level for research that cannot be easily accomplished without a mobile observational platform. The facility could be made available to users through an annual call for proposals, evaluated by a panel of researchers from the Swiss community, to participate in field campaigns and to test and validate new instruments. Such a platform, with a standard suite of instrumentation, could be supplemented by specialized instruments provided by Swiss researchers and groups (throughout the ETH-domain, University system, and other stakeholders) on a per-campaign basis.

A second pool of instruments shall focus on the below-ground processes. This proposed pool should contain a sufficiently large number of five kinds of instruments: 1) broad-band seismometers for structural seismology, earthquake locations, etc.; 2) numerous (thousands of) nodal seismometers for sub-surface imaging and monitoring of landslides and glaciers; 3) fiber-optics to monitor fault zones, aquifers, permafrost thawing (thermokarst collapse), etc.; 4) accelerometers for monitoring anthropogenic effects; and 5) a comprehensive seismic reflection survey instrument pool, including sources, shared as a formalized pool across the country. Part of these sensors shall act as a fast-response task force in case of immediately imminent or ongoing events. Further, shared geophysical devices sensitive to below-ground effects should include 1) borehole instrumentation including downhole logging and on-site monitoring tool; 2) tilt meters and strain meters; 3) modern and multipronged electro-magnetic surveying pool; and 4) one of the new types of portable gravimeters that are currently being developed. These would allow an improved mapping of subsurface structures and a better evaluation of the various type of interactions taking place between the deep Earth and the surface.

To a large extent, the sensor types from both pools are complementary. Combining them will lead to a substantial amount of new knowledge. This proposed GeoMOBILE should be complemented by a variety of drones and carrier unmanned vehicles. These are required for repeated and frequent sampling of regions that are not immediately accessible, e.g., to investigate collapsed mountain flanks, glacier dynamics, changes on mountain tops or volcano summits, and other aspects of the hydrosphere, which is a key component of the geospheres, and is crucial for the Alpine region. Major challenges in the field of hydrology concern the measurement of precipitation, which shows an extremely high spatio-temporal variability in mountainous regions, but also soil moisture with its fundamental role in flood run-off generation, flooding, erosion control and sediment transport. In this context a drone-based, high-throughput tree phenotyping platform, with multiple sensor arrays that provide tree and stand-based information on structure and function, would help to elucidate the role of the vegetation interface in reducing such natural hazards.

11.3 Pillar III — The Swiss Geo-TIME facility

To decipher timescales and rates in Earth and environmental sciences we propose the Swiss Geo-TIME facility, intended to a) consolidate the existing structure and to b) endorse the possibility of creating a consortium of larger laboratories and multi-user facilities. This RI will interact with the proposed synchrotron-based facilities (see the Photon Science roadmap) to investigate timescales and rates across the scales from decades over millennia to billions of years. This will include emerging and new chronometers including those that record processes operating on short timescales near the Earth surface. Even more importantly, it would support a team of experts to run and develop these instruments, as this is absolutely necessary to obtain meaningful results from these state-of-the-art instruments. It is also essential to drive the development of new instruments and methodology, and support community efforts to improve the precision of decay constant measurements, increasing ionization efficiency in mass spectrometers and inter-method and inter-laboratory calibration. This facility, coordinated with a Switzerland-wide organization committee shall be equipped with the state-of-the-art instruments (with ever-increasing capabilities), including 1) Thermal ionization mass spectrometers (TIMS) for high-precision chronometry using radiogenic isotopes (U-Pb, Re-Os, Rb-Sr), 2) noble gas isotope ratio mass spectrometers (NG-IRMS, Ar-Ar, cosmogenic isotopes, He, Ne), 3) Secondary Ion Mass spectrometers, which require additional developments for the primary ion sources capable of producing stable, highly focused beams to provide constant and reproducible sputtering conditions, multicollection at low ion currents, and further developments in achieving sub-nanometer depth resolution with EXtreme Low Impact Energy SIMS, 4) optically stimulated luminescence and electron spin resonance dating facilities that allow age constraints of Quaternary sedimentary and thermal histories, and 5) Argon Trap Trace Analysis (ArTTa) that can be applied to environmental studies to study timescales of groundwater transport and dating of glacial samples on decadal to millennial timescales.

The new infrastructure will be equipped with new technologies that are emerging and/or are essential for significant advances related to the determination of timescales and rates in the Earth and environmental sciences. Specifically, it is fundamental to understand the internal mechanisms and structure of minerals that are the gateway to understand timescales and rates. All applications that determine timescales and rates would benefit from the acquisition of complementary geochemical and structural information gathered from various methods. These include, for example, focused ion beam (FIB) preparation of minerals combined with analytical Transmission Electron Microscopy (TEM), Micro-Fourier Transform Infra-red spectroscopy (FTIR) and Raman mapping facilities, or atom-probe tomography, or synchrotron-based facilities (detailed in the Photon Science roadmap). This facility would also need a solid and stable platform of key work-horse instruments: electron and secondary electron microprobes (EMP-SEM), and inductively coupled mass spectrometry (ICP-MS). Some of them should include in-situ lasering capabilities which are indispensable for the characterization of samples and will provide access to developing the most novel techniques (e.g., in-situ dating of multiple different mineral phases). For short timescales, C-H-N-O stable isotope facilities to understand environmental changes from millennial (sediments, tree rings, ice cores, speleothems) to daily timescales (atmospheric water vapor, plant photosynthates). Building such a research infrastructure that combines quantitative calculations with cutting edge instrumentation is bound to lead to important breakthroughs.

Our overarching goal is an easily accessible research network/facility working on times and rates on all scales relevant for the Swiss Earth and environmental science research community. To reach this ambitious goal, this Swiss Geo-TIME facility must: 1) house a large array of state-of-the-art analytical tools, both as a virtual umbrella to existing instrumentation in different places of Switzerland, as well as new instruments not yet available in Switzerland; 2) hire top-level staff to run the facility, in order to maintain the necessary laboratory conditions required for exciting, cutting-edge research in the next 10–20 years. Potential integration strategies with existing facilities need to be developed.

11.4 Pillar IV — Data Infrastructure for the Geosciences

The recent years have shown an increase in the amount and complexity of geoscientific data. This trend leads to a large diversity of data types and repositories, which impedes integrated geoscientific research. The proposed data infrastructure for the geosciences (Geo-DATA) is envisioned to tackle this challenge by serving as the central Swiss hub for the harmonization, access, management and analysis of geoscientific data, while complying with the FAIR data principles [1]. It will consist of two distinct conceptually separate, yet technically connected entities, the virtual data infrastructure for the geosciences (VDIG) tailored to digital, georeferenced geoscientific data (e.g., sensor timeseries, GIS data, simulation results, remote sensing imagery, 3D geological models) and the physical data infrastructure for the geosciences (PDIG) tailored to physical, georeferenced geoscientific samples (e.g., cores, rock specimen).

11.4.1 VDIG: Virtual Data Infrastructure for the Geosciences

The VDIG needs to be capable of integrating digital geoscientific datasets in all their dimensions and from all geoscientific disciplines irrespective of resolution or scale, and the concrete data type. All types of data should be embedded in a common reference system in a lossless manner. For specific applications, rapid, real-time data centralization from the field sites, as well as rapid retrieval are mandatory. The VDIG should furthermore take access rights into account, enabling users to protect their data, but, more importantly, to motivate them to share and combine data.

Due to the fact that the research infrastructure would be used by a large number of scientists in different fields of expertise using different types of data, storage platforms and processing methods, a federated approach is suggested: The research infrastructure should provide central data integration and storage capacities for users without their own storage capabilities, but should also enable users to maintain and link their own decentralized client-based data storage capabilities into the overall system. A broker module would allow the referencing and linking of all internal and external data sources. Appropriate FAIR[1] conforming metadata management of all data sources will be essential to ensure the operability of the broker module. Further main components of VDIG would deal with data retrieval and with distributed and centralized data management. Ideally, the VDIG should be built on top of existing infrastructure maintained by Swiss institutions like SWITCH[13] and CSCS[86] and it should seek coordination and integration with global initiatives such as EOSC[59] and EarthCube[52].

Ultimately, it is envisioned that the entirety of VDIG would be a digital representation of the natural space in the sense of the comprehensive 'Digital Earth'[87, 88]. Such a 'Virtual Geo-Switzerland' would be a permanently evolving, extended, and refined digital reproduction of the geo-environment in all dimensions and would allow multidimensional geoscientific and environmental entity, phenomena and process monitoring. It would not only incorporate functionality for data cleaning, harmonization, and data interoperability, but also provide interfaces to allow the development of tools for analytical, modelling, simulation and visualization tasks.

11.4.2 PDIG: Physical Data Infrastructure for the Geosciences

Across the Swiss Geosciences community, there is also the need for physical sample storage and curation facilities (see Box 15). Such sample storage in centralized physical repositories will not only ensure long-term accessibility but also steer national/international cooperation and provide training material for the next generation of scientists. Notwithstanding, systematic sample storage and identification is an undisputed necessity to provide the opportunity to test the robustness of results and to guarantee that results can be replicated, which will require a close link to the Research Data Alliance[58], the European Open Science Cloud[59], and the planned GEO Knowledge Hub. Moreover, managing and centralizing physical subsurface data will facilitate discussions at the national level regarding the management of geothermal energy resources, water exploitation, radioactive waste disposal, and the transportation grid. Also, in light of accelerated climate change, available core data need to be centralized as they provide crucial information on the subsurface, i.e., archives of past climate and environmental change necessary to paint more concrete narratives for how a future climate may manifest itself globally but also locally in Switzerland (extreme droughts, waning of the cryosphere, pertained access to water resources, changes in the geobio-ecosystems, tipping points in the climate system). Centralizing this hands-on core information will give data and tools to the government to develop future climate strategies. In addition, the rapid technological and methodological advancement of the tool set employed in the geosciences often enables the refinement and/or generation of more robust results as well as testing of novel methodology on well characterized sample materials.

PDIG requires sufficient capacity to store core sections and samples produced in the course of one generation (e.g., ~50 years) while being located in a central and easily accessible location in Switzerland. From an infrastructure perspective such a repository should at least feature the following: 1) capacity for several kilometers of refrigerated (4 ± 1 °C) cores; 2) capacity for several kilometers of non-refrigerated hard-rock cores and samples; 3) a freezer room (-20 ± 1 °C) for the long-term storage of frozen cores, high-priority samples for nucleic-acid (DNA etc.) or other temperature-sensitive analyses; 4) core cutting, sampling, and description facilities (including sufficient space for educational training and outreach activities); 5) core scanning facilities: whole and split core multi-sensor core logger, whole and split-core imaging (CT, linescan, hyperspectral), scanning XRF (elemental geochemistry); 6) a dedicated clean sampling laboratory for microbial DNA and sedimentary ancient DNA sampling; 7) mobile laboratory containers with infrastructure which can be deployed on land and at sea (e.g., mobile core logging and geomicrobiology laboratory).

Sample metadata and data originating from analyses performed on sample materials should be professionally managed in VDIG. In this way, physical sample materials along with metadata and auxiliary datasets are preserved. Based on current figures storage capacity for cores requiring refrigerated storage and samples requiring freezer storage (permafrost, freeze cores, DNA samples etc.) sufficient for a 50 years period the repository will require space on the order of 40,000–60,000 m^3.

The Alps
(photo: ESA, CC BY-SA 3.0 IGO)

12 Swiss Participation in International Organizations

Being a member of European Research Infrastructures (ERICs) allows Swiss institutions to gain access to international facilities that would not be possible otherwise. The following statements apply to most ERICs but the example of the ICOS-RI (Box 5) is showcased here as it is the most advanced with respect to integrated atmospheric research. ICOS participates in global initiatives such as the development of the Integrated Global Greenhouse Gas Information System (IG3IS)[89] of the WMO[63]. Furthermore, ICOS is recognized by the Subsidiary Body for Scientific and Technical Advice (SBSTA)[90] of the United Nations Framework Convention on Climate Change (UNFCCC)[91]. Ocean data in turn are connected to the Surface Ocean CO_2 Atlas (SOCAT)[92] and Global Ocean Data Analysis Project (GLODAP)[93], whereas atmospheric data are connected to the GAW program of the WMO. The GAW program is an international effort driven by the need to understand and control the increasing influence of human activity on the global atmosphere. Switzerland contributes to the quality management framework of the GAW program through the operation of a World Calibration Center[94] and a Quality Assurance/Science Activity Centre[95]. Additionally, Switzerland hosts three international mountain science networks: the Global Mountain Biodiversity Assessment (GMBA), the Mountain Research Initiative (MRI), and the Mountain Invasion Research Network (MIREN).

Regarding benefits, ICOS fosters Europe's scientific competence and competitiveness by strategically pooling available resources linked to greenhouse gas concentration and flux measurements. ICOS member and observer (Switzerland) countries receive support for their national inventories and capacity building. The standardization carried out in ICOS provides an example of the joint international efforts through which Europe has achieved global influence, and this plainly shows the strategic importance of ICOS. The high quality of reliable and comparable data is guaranteed by harmonized practices in the operations at its thematic centers and in the Carbon Portal data services used in data processing. Data produced within ICOS-RI are open access through the Carbon Portal and are free of charge even for commercial use.

Long-Term Forest Ecosystem Research (LWF; Box 3) has been conducted by WSL since 1994. These plots are part of several national and international networks, including ICP Forests, eLTER, Swiss FluxNet and ICOS. Two sites provide unique long-term manipulation experiments (Pfynwald[84]/irrigation and Davos Stillberg[85]/CO_2 fumigation).

Since 2018 the Swiss eLTER plots are on the European Roadmap for Research Infrastructure (ESFRI).

The financing of the SwissOGS (Box 12) should also be secured on a long-term basis as it participates in many global observing networks and in international organizations, such as IAG, GGOS, IGS, and ILRS. It serves as the reference point for all positioning and georeferencing in Switzerland and delivers long-term series of geodetic and geophysical parameters since almost seventy years. Furthermore, Switzerland actively participates in earth observation programs such as GEO[96].

To maintain and further strengthen the internationally visible Swiss scientific expertise in drilling and coring initiatives on the continents and in the oceans, the Swiss membership fees in the international joint drilling programs IODP and ICDP (Boxes 1 and 2) should be maintained and secured in the long term. This will guarantee that Swiss scientists can continue and develop further outstanding research in exploring Earth through scientific drilling, both tackling internationally defined strategic drilling objectives and flagship initiatives (such as ground-truthing future climate change, probing the deep Earth, assessing georisks and hazards, diagnosing ocean health, understanding better the tipping points and feedbacks in the Earth system, etc.). Through this, Swiss scientists will be granted continued access to unique and large-scale drilling infrastructure and platforms. Additionally, one dedicated priority and fast-response funding channel for scientific drilling related research projects and/or Swiss participation to other coring/sampling campaigns/expeditions at land/sea (e.g., organized through the Eurofleets Program and/or through the invitation of Swiss scientists to other drilling/coring platforms) will guarantee continuity in geo- and environmental research necessary to cope with the challenges on a changing Planet with limited resources.

Similarly, a continued active participation in EPOS (Box 14) is a sine qua non condition to benefit from the solidly established European collaboration network for a wide range of solid Earth themes, ranging from seismology to volcanos, multi-scale laboratories and 4-D geology. These will take place both in the field, such as forthcoming large broadband seismology experiments, and in the labs, with more transparent and compatible cooperation possibilities between institutions. As such, it is an outstanding opportunity for Swiss Geo-MOBILE pools to synchronize at the European scale wherever feasible.

13 Conclusions

The current state of Swiss geoscientific research is characterized by the fact that several research groups, laboratories, platforms, and data bases are running in parallel to provide state-of-the-art research support in Earth sciences investigations. Progress in understanding past and future Earth system changes, and managing the current Earth system, is challenged by fragmented and dispersed discipline-specific research. In the future, Earth science research should be developed towards a whole-system integrated and long-term understanding of the complex interactions among geospheres and the biosphere in the Earth system to provide guidance to society to manage its impact on socio-economies worldwide.

The strengths of the Swiss geosciences research are and have been:

→ the availability of long-term and stable funding

→ the strong link between basic research and education

→ the strength and unprecedented value of long-term observations and monitoring in the past

→ the fact that Switzerland is strongly connected internationally

→ research related to alpine environments, to a healthy environment and to sustainable use of natural resources has a global reputation in the geosciences

The consolidated recommendation of the geoscientific community to policy makers is that the geosciences require addressing the impressive breadth of topics in order to deal with the Earth as a system. It is recommended to strengthen the multidisciplinary nature of the geosciences by putting all activities under the roof of the **Integrated Swiss Geosciences** (Fig. 1) supported by four research infrastructure pillars.

In **Pillar I**, we strongly recommend to support ongoing and emerging internationally well embedded research programs (ACTRIS, ARES, eLTER, EPOS, GAW, GCW, HFSJG, ICDP, ICP Forests, ICOS, IODP, LWF, SwissOGS) to further strengthen the Swiss geosciences in these fields with high global visibility and Swiss reputation. In addition, we propose to widen and strengthen geoscientific research via an Integrated Long-term Observatory (Geo-OBSERVE) which is designed to be a complementary short- and medium-term monitoring network at the regional scale, targeting areas of Swiss Earth system interactions, from solid Earth to the environment and human influences, but also including the abovementioned RIs as a backbone infrastructure.

Pillar II proposes the establishment of a Mobile Monitoring Infrastructure (Geo-MOBILE) in which diverse, top-quality sensors can be used at various sites, and large sensor networks are made available for spatially explicit investigations of important research topics in the geosciences, such as aerosol impacts on ecosystems, public health, climate and earthquake risks, as well as transients in a broad range of processes.

Pillar III proposes to build a new infrastructure related to timescales and rates of geoscience processes (Geo-TIME). This requires developing new technologies and facilities fully open to Swiss Geoscientists and it will revolutionize our capabilities to quantify rates of geoscientific processes from the anthropocene to deep time. This requires novel infrastructures (instrumentations) and highly qualified staff for operation and maintenance. The Geo-TIME facility provides the services to geoscientists to fully benefit from such state-of-the-art technology.

Pillar IV proposes to establish an integrated digital and physical Data Infrastructure for the Geosciences (Geo-DATA), which would allow for comprehensive data management, harmonization, storage and curation as well as would support sophisticated analyses, visualization, modelling and simulation tasks. This will serve as a virtual laboratory environment that is required for ground breaking research of the community while also providing a central sample storage facility for professional curation of geoscientific sample materials along with their metadata.

The present roadmap is the first geosciences community-based roadmap and represents the first consolidated view of the key findings and recommendations by many Swiss geoscientists on how to develop large geoscientific research infrastructures during 2025 – 2028 in Switzerland. It is also a first step in the direction of bringing the different subdisciplines together under a common roof supported by common large research infrastructure needs. This fruitful interaction among geosciences disciplines would greatly benefit if the research community can be involved in a similar way also in future roadmaps for geosciences research infrastructures.

14 Abbreviations

ACTRIS	Aerosols, Clouds and Trace gases Research Infrastructure
AGNES	Automated GNSS Network for Switzerland
AlpArray	a European initiative to advance our understanding of orogenesis and its relationship to mantle dynamics, plate reorganizations, surface processes and seismic hazard in the Alps-Apennines-Carpathians Dinarides orogenic system
ARES	Airborne Research facility for the Earth System
CLRTAP	Convention on Long-Range Transboundary Air Pollution
COGEAR	Coupled seismogenic GEohazards in Alpine Regions
COST-G	the international Combination Service for Time-variable Gravity fields
COVID-19	Coronavirus disease 2019
cryo-NanoSIMS	a SIMPS that can isotopically image cryogenized organic samples with ultra-high spatial resolution
CSCS	Swiss National Supercomputing Centre
CT	Computed Tomography
DNA	Deoxyribonucleic Acid
eLTER	Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research Infrastructure
EPOS	European Plate Observing System
ERI-Dispatch	dispatch on the promotion of Education, Research and Innovation presented by the Swiss Federal Council to the Parliament
ERIC	European Research Infrastructure Consortium
ESA	European Space Agency
ESFRI	European Strategy Forum on Research Infrastructures
EUDAT	a pan-European network consisting of more than 25 research organizations, data and computing centers
EUROCHAMP	a European project which aims a better integration of simulation chambers for studying atmospheric processes
FAIR	data that meet the principle of Findability, Accessibility, Interoperability, and Reusability
FSDI	Federal Spatial Data Infrastructure
GAW	Global Atmosphere Watch
GCW	the World Meteorological Organization's Global Cryosphere Watch
GEO	Group on Earth Observations
Geo-DATA	Data infrastructure for the geosciences (the 4th pillar in the present roadmap)
Geo-MOBILE	mobile infrastructure for temporary monitoring (2nd pillar in the present roadmap)
Geo-OBSERVE	Integrated Long-term Geo-Observatory (the 1st pillar in the present roadmap)
Geo-TIME	distributed facilities network for dating geo-events (the 3rd pillar in the present roadmap)
GGOS	Global Geodetic Observing System
GLOBE	the Global Learning and Observations to Benefit the Environment program is an international science and education program
GNSS	Global Navigation Satellite System
H2020-INFRADEV	European Horizon 2020 Research Infrastructure Development Program
HFSJG	High Altitude Research Stations Jungfraujoch and Gornergrat
IAG	International Association of Geodesy
IAP	Institute for Applied Plant Biology
ICDP	International Continental Scientific Drilling Program
ICOS	Integrated Carbon Observation System
ICOS-RI	Integrated Carbon Observation System Research Infrastructure
ICOS-CH	Integrated Carbon Observation System Switzerland
ICP Forests	International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on Forests
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
IGS	International GNSS Service
ILRS	International Laser Ranging Service
iLTER	International Long-Term Ecological Research Network
INSPIRE	Infrastructure for Spatial Information in the European Community
IODP	International Ocean Discovery Program
LWF	Long-Term Forest Ecosystem Research (Langfristige Waldökosystemforschung)
MINT	Mathematics, Informatics, Natural sciences, Technics
NABEL	National Air Pollution Monitoring Network
NAGRA	the Swiss technical competence center in the field of deep geological disposal of radioactive waste
OGC	the Open Geospatial Consortium
OLOS	a digital repository solution for long-term preservation and publishing of research data for all Swiss academic research institutions
PDIG	Physical Data Infrastructure for the Geosciences (part of the 4th pillar in the present roadmap)
PMOD/WRC	Physical Meteorological Observatory in Davos / World Radiation Centre
PSI	Paul Scherrer Institute (ETH-Domain)
RI	Research Infrastructure
RIs	multiple Research Infrastructures

SCNAT	Swiss Academy of Sciences
SED	Swiss Seismological Service
SERI	State Secretariat for Education, Research and Innovation
SIMS	Secondary-Ion Mass Spectrometry
SLR	Satellite Laser Ranging
SNSF	Swiss National Science Foundation
SRfRI	Swiss Roadmap for Research Infrastructures
SwissBioColl	Planned RI for the digitization, curation and coordination of natural history collections and biobanks as described in the Biology roadmap
SwissCollNet	Swiss Natural History Collections Network
SwissOGS	Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald
swisstopo	Swiss Federal Office of Topography
swissuniversities	The umbrella organization of the Swiss universities
SWITCH	a foundation that operates the Swiss research and education network
TIMS	Thermal ionization mass spectrometry
UN-FAO	United Nations Food and Agriculture Organization
UN-GGIM	United Nations Committee of Experts on Global Geospatial Information Management
UNECE	United Nations Economic Commission for Europe
US	United States of America
UV	ultraviolet light
VDIG	Virtual Data Infrastructure for the Geosciences (part of the 4th pillar in the present roadmap)
WMO	World Meteorological Organization
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research (ETH-Domain)
XRF	X-ray fluorescence

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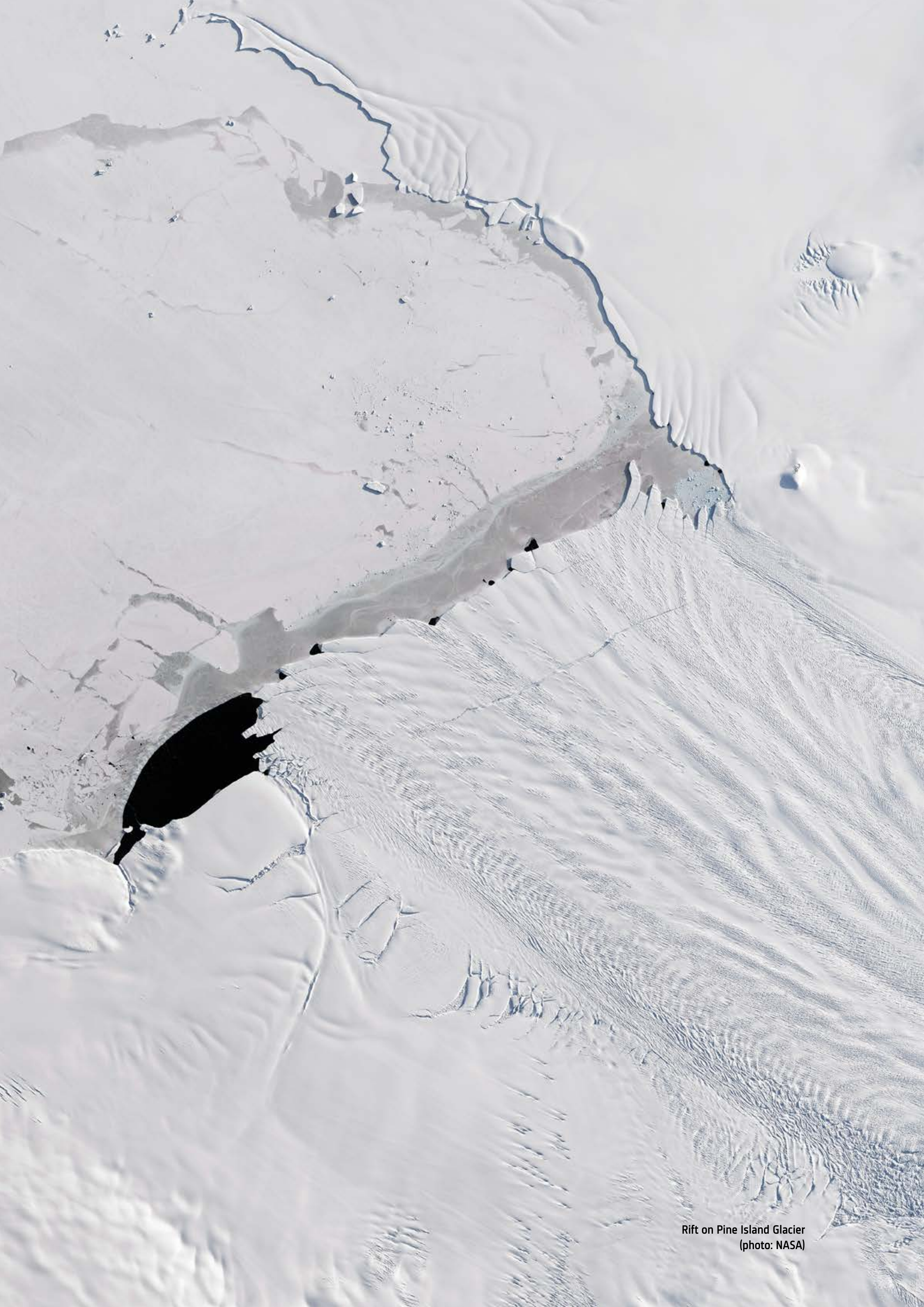

Rift on Pine Island Glacier
(photo: NASA)

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